ESC-TR-2007-054

Project Report
ATC-337

Elementary Surveillance (ELS) and Enhanced Surveillance (EHS) Validation via Mode S Secondary Radar Surveillance

R.D. Grappel
G.S. Harris
M.J. Kozar
R.T. Wiken

23 April 2008

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Prepared for the Department of the Air Force under Contract FA8721-C-05-0002.

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. This work was sponsored by the Defense of Defense under Air Force Contract FA8721-05-C-0002.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Gary Tutungian
Administrative Contracting Officer
Plans and Programs Directorate
Contracted Support Management

Massachusetts Institute of Technology
Lincoln Laboratory

Elementary Surveillance (ELS) and Enhanced Surveillance (EHS) Validation via Mode S Secondary Radar Surveillance

R.D. Grappel
G.S. Harris
M.J. Kozar
R.T. Wiken
Group 42

Project Report ATC-337

23 April 2008

Lexington Massachusetts

EXECUTIVE SUMMARY

Several applications of the Mode S data link are currently being implemented and equipage requirements have been issued in countries around the world. Elementary surveillance (ELS) and Enhanced surveillance (EHS) applications have been mandated in Europe with full equipage of all aircraft in the airspace required by 2009. Exemptions to the ELS requirement include aircraft that will be out of service by 31 December 2009, and aircraft undergoing flight-testing, delivery, or transit into or out of maintenance bases. Transport type aircraft (defined as having a maximum take-off weight in excess of 5700 kilograms (about 12,500 pounds) or a maximum cruising airspeed in excess of 250 knots) are to be equipped to support ELS and EHS. Exemptions to the requirement for EHS include those listed above for ELS and:

(a) Fighter and training aircraft;

(b) Rotary-wing aircraft;

(c) Existing/older transport type aircraft undergoing avionics upgrades which will then support ELS/EHS; and

(d) Aircraft types granted special exemptions (e.g., B1-B, B2-A, and B-52H bombers).

The automatic dependent surveillance via broadcast application (ADS-B, using Mode S 1090 MHz squitter as the link) is already in place in some countries (e.g., Australia) and a notice of proposed rule-making has been issued in the U.S. to require ADS-B equipage in all aircraft by 2020. The United States Air Force (USAF) has taken notice of the current and proposed requirements for Mode S avionics and is actively equipping its fleet for the appropriate Mode S applications so that its aircraft will conform to the requirements in all airspace where they might need to operate. Lincoln Laboratory was tasked by the USAF to develop an approach to avionics monitoring to ensure that its installed Mode S data link avionics are operating in conformance with the requirements of these applications. This report was written to describe the algorithms and methodology required to determine conformance for the ELS and EHS applications. A separate report is being written for the ADS-B application.

As illustrated in the simplified block diagram shown in Figure 1, the avionics required to support the Mode S data link applications consist of a number of data sources, several functional blocks, a Mode S transponder, and several data buses and interconnections. (Note: the blocks marked with an asterisk are optional and might be combined with other blocks, e.g., the data concentrator/formatter functionality might be incorporated into the Mode S transponder.) While there are independent unit tests required for each avionics block, what is needed to ensure proper operation of the complete system is a test procedure covering the entire system.

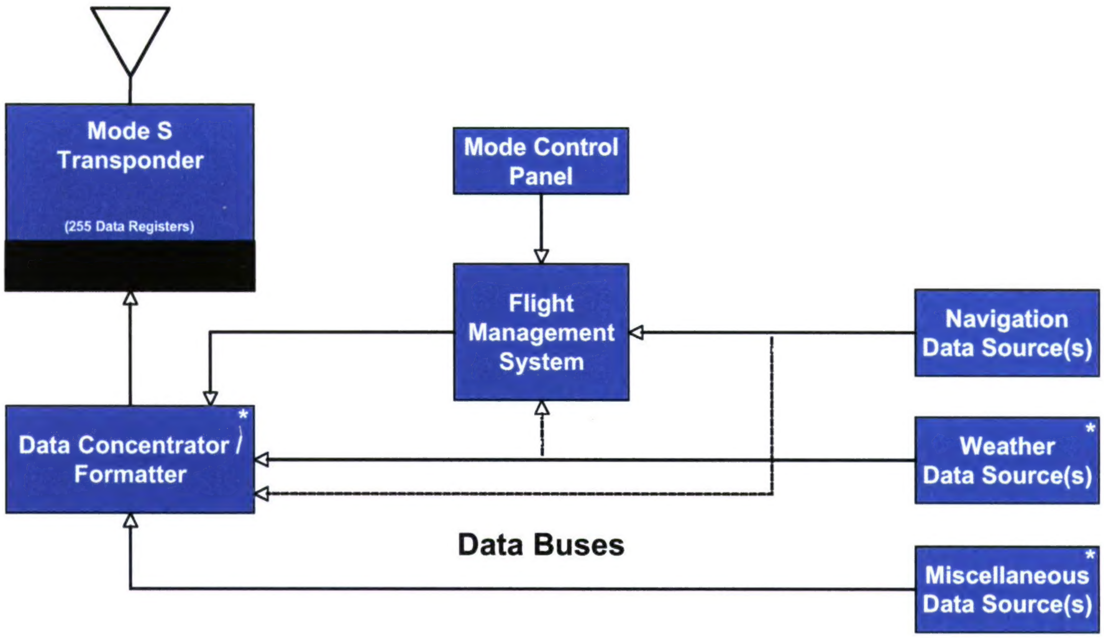


Figure 1. Simplified Mode S Avionics Architecture.

One overall system test methodology that has been proposed uses an external test jig that can insert known data onto the aircraft's data buses. The output of the Mode S transponder would be validated against the expected results arising from the injected values. This test methodology has the following drawbacks:

(1) It requires a specific knowledge of the buses and installed equipment on the aircraft. Differing procedures would be required for different configurations. Not all USAF aircraft employ the same interconnecting buses (or they might not provide convenient data ports for the connection of the necessary test apparatus). Aircraft-specific test equipment might be required (e.g., to bypass the aircraft's weight on wheels switch).

(2) It can only deal with one subject aircraft at a time. There would need to be considerable management and scheduling of the test processing to make sure that sufficient numbers and types of aircraft were tested.

(3) Since there are many data items incorporated into the Mode S applications (and some of these data items are inter-related), it would take quite a large test set to fully cover the possible cases. Unexpected/unanticipated system errors or failure modes might be missed.

(4) A one-at-a-time test methodology is not useful for monitoring the overall conformance of the USAF fleet. It would not detect failures or anomalies that occurred after the testing for the aircraft type had been completed or which were specific to a particular aircraft.

(5) The end-users of the Mode S applications will be validating the performance of the applications from actual flight operations.

Responding to these drawbacks of testing compliance via data insertion (especially (4) and (5)), Lincoln Laboratory is developing a fleet monitoring system whose overall architecture is

shown in Figure 2. A Mode S sensor on the ground is employed to obtain surveillance data to support construction of "truth tracks". The same sensor uses the Mode S data link to extract the contents of particular transponder registers from the aircraft within its surveillance. This transponder register extraction protocol is entirely equivalent to the procedure that the actual users of the Mode S applications will employ. The monitoring system compares the extracted register data with the Mode S surveillance data truth tracks and flags any deviations deemed significant. The fleet monitoring system can be used to determine compliance for a single aircraft (identified by its unique Mode S address), to monitor all aircraft in sensor coverage, or to validate a range of aircraft in the airspace (e.g., all U.S. military aircraft). The fleet monitoring system requires no additional equipment onboard the aircraft or within the Mode S sensor.

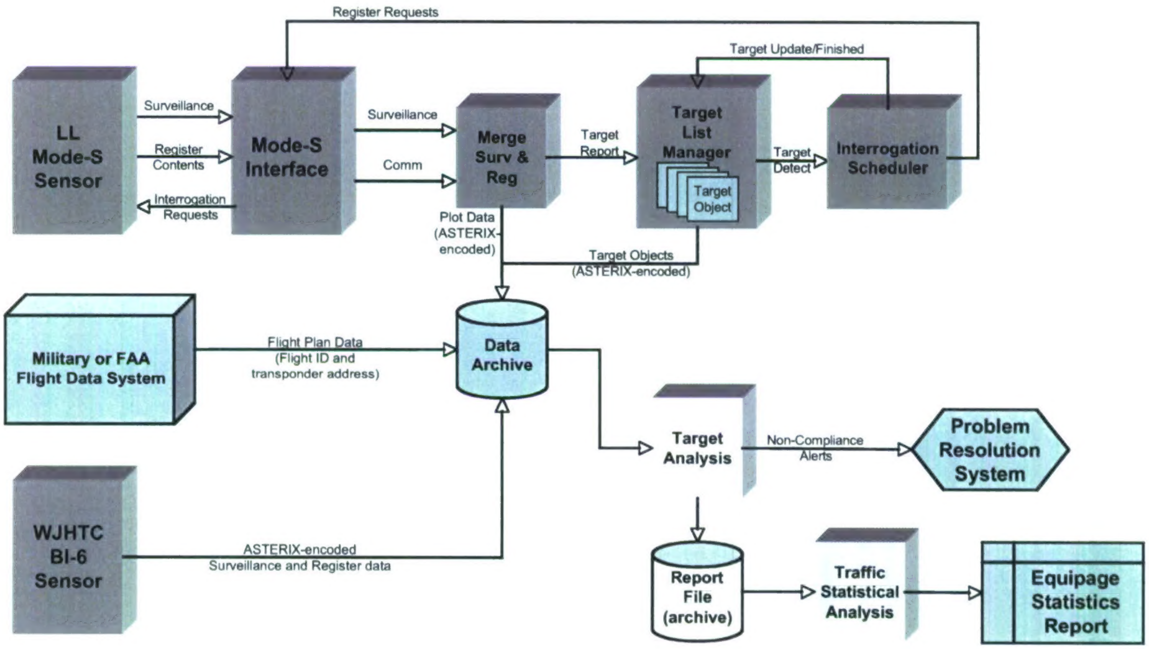


Figure 2. Fleet Monitoring System Architecture.

Note: it is assumed that each component of the individual aircraft avionics has already passed its bench and ramp tests. The compliance monitoring described in this report is intended as a full-system evaluation of the performance of the Mode S data link application avionics. Additionally, some data elements of specific applications may require truth data that cannot be obtained via the Mode S sensor surveillance. For example, the aircraft's flight identification would need to be determined from external sources (e.g., the flight plan) in order to fully validate this data field. As another example, the Mode S surveillance data can be used to determine the aircraft's *ground* speed – but the aircraft's *airspeed* values are influenced by the local winds (and other factors). While it may be possible to infer or independently obtain the wind data, full validation of the airspeed would require an actively controlled test plan including the participation of the pilot.

This report is aimed at an engineering team tasked with implementing an automatic analysis system to perform ELS/EHS compliance monitoring. The material covered in this report includes the following areas of the ELS/EHS monitoring process:

(a) Definitions for the data link interface to a Mode S sensor and the protocols to be used in extracting data from aircraft transponders;

(b) Examination of the avionics configuration and status information for ELS and EHS;

(c) Examination of the ELS aircraft identification and ACAS registers;

(d) Computation of the acceptability thresholds for surveillance-based EHS data (e.g., ground speed, turn rate) based on the measurement accuracy of the Mode S sensor being used for the monitoring;

(e) Horizontal and vertical tracker algorithms (derived from Mode S applications) used to derive velocity components from Mode S sensor target reports;

(f) Algorithms used to check EHS airspeed values for consistency; and

(g) Validation of the EHS register's dynamic values.

It should be noted that the focus of this report is a compliance *monitoring* system. This report does not include descriptions of such *test* system components as test director stations and real-time data processing, or definitions of any controlled flight tests or specific test scenarios that might be deemed necessary to fully exercise the Mode S ELS and EHS application avionics in a flight test environment.

TABLE OF CONTENTS

Executive Summary		iii
List of Illustrations		xi
List of Tables		xii
1.	INTRODUCTION	1
	1.1 References	4
	1.2 Document Organization	5
	1.3 Compliance Verification Methodology	6
	1.4 Semantics of the Tests	7
	1.5 Surveillance Basics	8
2.	CONFIGURATION VALIDATION	11
	2.1 Capability (CA) Field Validation	11
	2.2 Capability Register Validation	11
	2.3 Common-Usage Register Validation	14
	2.4 Data Link Capability Register Validation	15
3.	CALCULATION OF VALIDATION THRESHOLDS	19
	3.1 Assumptions	19
	3.2 Inputs	19
	3.3 Derived Intermediate Terms	20
	3.4 Calculating Heading Sigma	22
	3.5 Calculating Ground Speed Sigma	23
	3.6 Calculating Heading-Rate Sigma	24
	3.7 Calculating Roll-Angle Thresholds	25
	3.8 Calculating Altitude Rate Thresholds	25
4.	FLIGHT STATUS (FS) VALIDATION	27
5.	AIRCRAFT IDENTIFICATION (REGISTER 20_{16}) VALIDATION	31
6.	ACAS ADVISORY (REGISTER 30_{16}) VALIDATION	33
7.	SELECTED VERTICAL INTENTION (REGISTER 40_{16}) VALIDATION	35

TABLE OF CONTENTS (Continued)

8. TRACK AND TURN (REGISTER 50_{16}) VALIDATION 39

- 8.1 Roll Angle 40
- 8.2 True Track Angle 41
- 8.3 Ground Speed 44
- 8.4 Track Angle Rate 45
- 8.5 True Airspeed (TAS) 46

9. HEADING AND SPEED (REGISTER 60_{16}) VALIDATION 49

- 9.1 Magnetic Heading 50
- 9.2 Indicated Airspeed (IAS) 52
- 9.3 Mach 53
- 9.4 Barometric Altitude Rate 55
- 9.5 Inertial Vertical Velocity 57

APPENDIX A: MODE S REGISTER LAYOUTS FROM ICAO DOC 9871 59

APPENDIX B: EXAMPLE HORIZONTAL TRACKER ALGORITHMS 71

- B.1 Real-Time Horizontal Tracker 71
- B.1.1 Initialization State 73
- B.1.2 Second Report State 73
- B.1.3 Mature Track State 73
  - B.1.3.1 Smoothing/Prediction 74
  - B.1.3.2 Turn Sensing 75
- B.2 Non-Real-Time Horizontal Path Smoother 77
- B.2.1 Outlier Removal Pass 77
  - B.2.2 Smoothing Pass 78
  - B.2.3 Quadratic Curve-Fit Algorithm 79

APPENDIX C: 100 FOOT FLIGHT LEVEL VERTICAL TRACKER ALGORITHM 83

- C.1 Vertical Tracker Driver/Handler 84
- C.2 Initialization State 86
- C.3 No Transition State 86
- C.4 Transition State 87
- C.5 Reset Smoothing State 88

APPENDIX D: 25 FOOT ALTITUDE TRACKER ALGORITHM 91

APPENDIX E: NON-REAL-TIME VERTICAL POSITION SMOOTHING ALGORITHM 93

TABLE OF CONTENTS (Continued)

APPENDIX F: RELATIONSHIPS AMONG GROUND SPEED, IAS, TAS, AND MACH 95

APPENDIX G: THE MODE S METEOROLOGICAL AIR REPORT (REGISTER 44_{16}) 99

APPENDIX H: THE FAA'S TERMINAL MODE S SENSOR COMMUNICATIONS INTERFACE DESIGN 101

H.1 Link-Level Protocols 101
H.2 Communications Interface Messages 102
H.2.1 Common Data Fields in non-ATC Communications Messages 102
H.2.1.1 Sensor Identifier 102
H.2.1.2 Message Number 102
H.2.1.3 Padding Bits 102
H.2.1.4 Type Code 103
H.2.2 Request-Response Messages 103
H.2.2.1 ATCRBS Mode 3/A Request-Response 104
H.2.2.2 Data Link Capability Request-Response 104
H.2.2.3 Aircraft Position Request-Response 105
H.2.2.4 GICB Downlink Request-Response 106
H.2.2.5 Broadcast Downlink 108
H.2.2.6 Determination of Mode S Addresses 110

APPENDIX I: THE ASTERIX CATEGORY 018 SURVEILLANCE AND DATA LINK INTERFACE 113

I.1 Common Data Items 113
I.1.1 Message Type 113
I.1.2 Mode S Address 113
I.1.3 Data Source Identifier 114
I.1.4 Data Destination Identifier 114
I.2 Aircraft Report (Surveillance Data) 114
I.2.1 Aircraft Report Request 114
I.2.1.1 Aircraft Data Link Command 114
I.2.1.2 Aircraft Data Link Report Request 115
I.2.2 Aircraft Data Link Report Response 116
I.2.2.1 Aircraft Data Link Status 116
I.2.2.2 Transponder Capability 117
I.2.2.3 Transponder Extended Capability Report 117
I.2.2.4 Aircraft Position in Polar Coordinates 118
I.2.2.5 Aircraft Position in Cartesian Coordinates 118
I.2.2.6 Aircraft Identification 118
I.2.2.7 Aircraft Mode 3/A Identity Code 118

TABLE OF CONTENTS (Continued)

I.2.2.8 Aircraft Altitude 118
I.2.2.9 Aircraft Speed 119
I.2.2.10 Aircraft Ground Track Angle 119
I.3 GICB Extraction (Data Link) 119
I.3.1 GICB Extraction Request 119
I.3.2 GICB Extraction Response 120
I.3.3 GICB Extraction Request Acknowledgement 122
I.3.4 GICB Extraction Cancellation 122
I.4 Downlink Broadcast 122
I.5 Format Summary 122

APPENDIX J: DERIVATION OF THE INTERMEDIATE TERMS FOR THRESHOLD VALIDATION CALCULATIONS 125

ACRONYMS 127

REFERENCES 129

LIST OF ILLUSTRATIONS

Figure No.		Page
1-1	Simplified Mode S Avionics Architecture	2
1-2	Fleet Monitoring System Architecture	3
1-3	Mode S Surveillance/Communications Data Formats	8
1-4	Format of ASTERIX Category 048 Data Item 250 (Mode S MB Data)	9
1-5	Mode S Register Architecture for ELS and EHS Data Link Applications	10
3-1	Relationship Between Ground Range/Azimuth and Cartesian X-Y Variances	21
8-1	Magnetic Declination for the U.S. (2004)	43
A-1	Data Link Capability Report (BDS Code 1,0)	60
A-2	Common Usage GICB Capability Report (BDS Code 1,7)	62
A-3	Mode S Specific Services GICB Capability Report (BDS Code 1,8)	63
A-4	Mode S Specific Services GICB Capability Report (BDS Code 1,9)	64
A-5	Aircraft Identification (BDS Code 2,0)	65
A-6	ACAS Active Resolution Advisory (BDS Code 3,0)	66
A-7	Selected Vertical Intention (BDS Code 4,0)	67
A-8	Track and Turn Report (BDS Code 5,0)	68
A-9	Heading and Speed Report (BDS Code 6,0)	69
F-1	Relationships Among CAS, TAS, and Mach Numbers for Varying Temperature and Altitude – Subsonic	97
F-2	Relationships Among CAS, TAS, and Mach Numbers for Varying Temperature and Altitude – Supersonic	97
G-1	Routine Meteorological Report (BDS Code 4,4)	100

LIST OF TABLES

Table No.		Page
4-1	Surveillance Status Codes and Definitions	27
5-1	Value Ranges for Flight Identification	31
7-1	Encoding of Target Altitude Source in Register 40_{16}	36
B-1	Horizontal Tracker Firmness Update for Coasting	72
B-2	Alpha, Beta, and Firmness Updates	74
B-3	THK Value as a Function of Track Firmness	76
H-1	Non-ATC Message Type Codes (subset for ELS/EHS)	103
H-2	Format of Message Rejection/Delay Notice	104
H-3(a)	Format of ATCRBS Mode 3/A Request Message	104
H-3(b)	Format of ATCRBS Mode 3/A Response Message	104
H-4(a)	Format of Data Link Capability Request Message	105
H-4(b)	Format of Data Link Capability Response Message	105
H-5(a)	Format of Aircraft Position Request Message	105
H-5(b)	Format of Aircraft Position Response Message	106
H-6(a)	Format of GICB Downlink Request Message	107
H-6(b)	Format of GICB Downlink Response Message	107
H-6(c)	Format of GICB Downlink with Position Response Message	108
H-7(a)	Format of Broadcast Downlink Message	109
H-7(b)	Format of Broadcast Downlink with Position Response Message	110
H-8	Format of Track Drop Message	111
I-1	ASTERIX Category 018 Message Type Encodings	113
I-2(a)	ASTERIX Category 018 Data Item 009 (Byte 1)	115
I-2(b)	ASTERIX Category 018 Data Item 009 (Optional Byte 2)	116
I-3(a)	ASTERIX Category 018 Data Item 008 (Byte 1)	117
I-3(b)	ASTERIX Category 018 Data Item 008 (Optional Byte 2)	117
I-4	ASTERIX Category 018 Data Item 030 (GICB Properties)	120
I-5	ASTERIX Category 018 Data Item 001 Cause Codes	121

LIST OF TABLES (Continued)

I-6	ASTERIX Category 018 Data Item 001 Diagnostic Codes	121
I-7	ASTERIX Category 018 Message Summary (for ELS/EHS applications)	123

1. INTRODUCTION

Several applications of the Mode S data link are currently being implemented and equipage requirements have been issued in countries around the world. The elementary surveillance (ELS) and enhanced surveillance (EHS) applications have been mandated in Europe with full equipage of all aircraft in the airspace required by 2009. (See [1] for a complete specification of the European ELS/EHS mandate.) Exemptions to the ELS requirement include aircraft that will be out of service by 31 December 2009, and aircraft undergoing flight-testing, delivery, or transit into or out of maintenance bases. Transport type aircraft (defined as having a maximum take-off weight in excess of 5700 kilograms (about 12,500 pounds) or a maximum cruising airspeed in excess of 250 knots) are to be equipped to support ELS and EHS. Exemptions to the EHS requirement include those listed above for ELS and:

(a) Fighter and training aircraft;

(b) Rotary-wing aircraft;

(c) Existing/older transport type aircraft undergoing avionics upgrades which will then support ELS/EHS; and

(d) Aircraft types granted special exemptions (e.g., B1-B, B2-A, and B-52H bombers).

The United States Air Force (USAF) has taken notice of the current and proposed requirements for Mode S avionics and is actively equipping its fleet for the appropriate Mode S applications so that its aircraft will conform to the requirements in all airspace where they might need to operate. Lincoln Laboratory was tasked by the USAF to develop an approach to avionics monitoring to ensure that installed Mode S data link avionics are operating in conformance with the requirements of these applications. This report was written to describe the monitoring algorithms and methodology required to determine conformance for the ELS and EHS applications[1].

As illustrated in the simplified block diagram shown in Figure 1-1, the avionics required to support the Mode S data link applications consist of a number of data sources, several functional blocks, a Mode S transponder, and several data buses and interconnections. (Note: the blocks marked with an asterisk are optional and might be combined with other blocks, e.g., the data concentrator/formatter functionality might be incorporated into the Mode S transponder.) While there are currently specific unit tests required for each avionics block independently, what is needed to ensure proper operation of the complete system is a test procedure for the complete system.

---

[1] The automatic dependent surveillance via broadcast (ADS-B) application (using Mode S 1090 MHz squitter as the link) is already in place in some countries (e.g., Australia), and a notice of proposed rule-making has been issued in the U.S. to require ADS-B equipage in all aircraft by 2020. ADS-B monitoring is addressed in a separate Report.

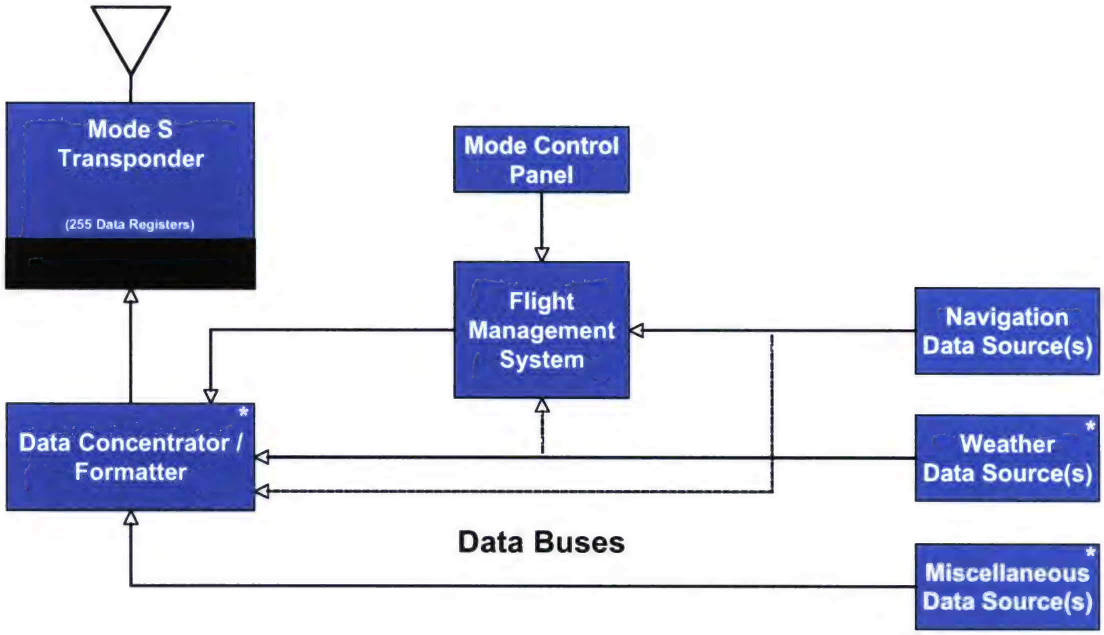


Figure 1-1. Simplified Mode S Avionics Architecture.

One overall system test methodology that has been proposed uses an external test jig that can insert known data onto the aircraft's data buses. The output of the Mode S transponder would be validated against the expected results. This test methodology has the following drawbacks:

(1) It requires a specific knowledge of the buses and installed equipment on the aircraft under test. Differing test procedures would be required for different configurations. Not all USAF aircraft employ the same interconnecting buses (or they might not provide convenient data ports for the connection of the necessary test apparatus). Aircraft-specific test equipment might be required (e.g., to bypass the aircraft's weight on wheels switch);

(2) It can only deal with one subject aircraft at a time. There would need to be considerable management and scheduling of the test processing in order to make sure that sufficient numbers and types of aircraft were tested;

(3) Since there are many data items incorporated into the Mode S applications (and some of these data items are inter-related), it would take quite a large test set to fully cover the possible cases. Unexpected/unanticipated system errors or failure modes might be missed;

(4) A one-at-a-time test methodology is not useful for monitoring the overall conformance of the USAF fleet on a continual basis. It would not detect failures or anomalies that occur after the testing for the aircraft type had been completed or which were specific to a particular aircraft; and

(5) The end-users of the Mode S applications are establishing a monitoring program to determine aircraft performance from actual flight operations.

Responding to these drawbacks of testing compliance via data insertion (especially (4) and (5)), Lincoln Laboratory is developing a compliance monitoring system whose overall

architecture is shown in Figure 1-2. A Mode S sensor on the ground is employed to obtain surveillance truth for the aircraft (one or many). Simultaneously, the Mode S sensor uses the data link to extract the contents of particular transponder registers from all aircraft. (Note: this transponder register extraction protocol is entirely equivalent to the procedure that the actual users of the Mode S applications will employ.) The fleet monitoring system compares the extracted register data with the Mode S surveillance data truth and flags any deviations deemed significant. Figure 1-2 illustrates the overall architecture used by Lincoln Laboratory to record the surveillance and register data for off-line analysis. The fleet monitoring system can be used to test a single aircraft (identified by its unique Mode S address), to monitor all aircraft in sensor coverage, or to validate a range of aircraft in the airspace (e.g., all U.S. military aircraft). The fleet monitoring system requires no additional equipment onboard the aircraft or within the Mode S ground sensor, with the only requirement being the connection of a modem to an existing sensor interface.

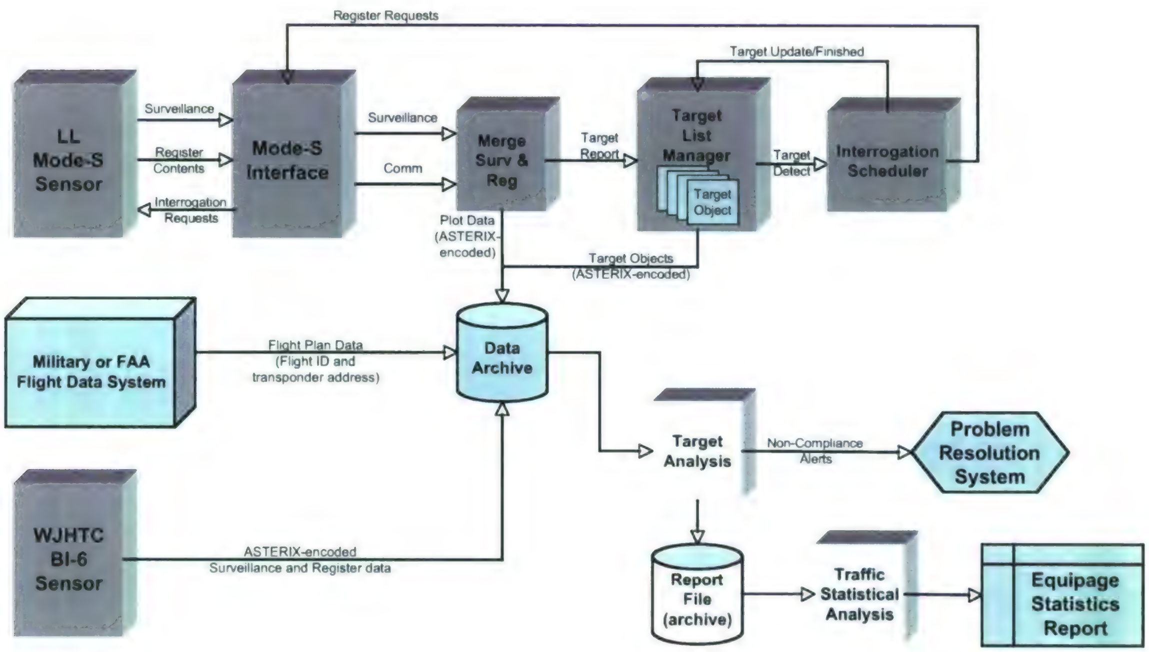


Figure 1-2. Fleet Monitoring System Architecture.

Note: it is assumed that each component of the individual aircraft avionics has already passed its bench and ramp tests. It is assumed that the Mode S transponder, encoding altimetry system and ACAS equipment (if one is installed) are each performing to specification. The fleet monitoring described in this report is intended as a full-system evaluation of the performance of the Mode S data link application avionics. Some data elements of specific applications may require truth data that cannot be obtained via the Mode S sensor surveillance. For example, the Mode S surveillance data can be used to determine the aircraft's *ground* speed – but the aircraft's *airspeed* values are influenced by the local winds (and other factors). While it may be possible to obtain or infer the wind data, full validation of the airspeed would require an actively controlled test plan including the participation of the pilot.

This report contains definitions for the data link interface to a Mode S sensor and the protocols to be used in extracting data from an aircraft's transponder. Algorithms for horizontal and altitude tracking of surveillance data are provided in order to compute aircraft velocities and accelerations. Procedures are defined to calculate the validation thresholds for various ELS and EHS data items based on the measurement accuracy parameters of the surveillance source. The sequence of steps required to evaluate the Mode S configuration state of an aircraft relevant to the ELS and EHS applications is specified. Finally, this report details the validation processing for each data field in each Mode S transponder register that is involved in the ELS and EHS applications.

The focus of this report is a compliance *monitoring* system, rather than an ELS/EHS *flight-test* system. Therefore, it does not include descriptions of such key test system components as test director stations and real-time data processing, or definitions of any controlled flight tests or specific test scenarios that might be deemed necessary to fully exercise the Mode S ELS and EHS application avionics in a flight test environment.

The intended audience for this report is an engineering staff assigned the task of implementing a monitoring system that can determine ELS and EHS compliance for an aircraft, either for a fleet or for a specific aircraft. This discussion assumes that standard surveillance truth data and Mode S ELS and EHS register data have been acquired using a Mode S ground sensor capable of extracting particular Mode S transponder registers via the Mode S ground-initiated Comm-B (GICB) protocol [1].

The algorithms described herein are intended for either real-time or off-line (recorded data) operation. They are capable of validating a large portion of the ELS/EHS avionics installation automatically – requiring no additional inputs or test procedures. They may involve a single selected aircraft up to and including all aircraft in the coverage of the sensor. Where additional data are required for a full test of the installation (such as flight identification), those inputs are described herein.

1.1 References

Reference [1] contains the European ELS and EHS mandate requirement specification. Reference [2] provides the full definition and international standards for Mode S-Specific services including ELS and EHS. Reference [3] provides a summary description for the ELS and EHS applications (along with the Automatic Dependent Surveillance via Broadcast (ADS-B) application).

Reference [4] is the source for most of the algorithms used to derive the measurement accuracy bounds for the various surveillance parameters as a function of the sensor performance. Reference [5] defines the various data fields in ASTERIX Category 048 surveillance output format that can be used where available from the supporting sensor. Reference [6] is the source of the horizontal and 100-foot vertical tracker algorithms in the appendices. References [7] and [8] provide the background for these algorithms.

Reference [9] provides the standards and test procedures for ACAS (a portion which is part of ELS). In addition, it describes a 25-foot altitude tracker, as described in Appendix D.

References [10] and [11] describe the relationships among the various measures of airspeed provided by EHS. Reference [12] illustrates the variance between magnetic and true north for the continental United States.

References [13] through [15] define the data link interfaces used by the terminal Mode S sensors fielded in the United States. References [16] and [17] define the internationally standardized ASTERIX Category 018 interface (surveillance and data link functions).

1.2 Document Organization

Section 2 of this report discusses the Mode S Communication Capability, as well as Static and Dynamic Configuration. It describes the process of determining whether the transponder is capable of supporting register data extraction and whether the transponder asserts that ELS and EHS data items are available via register extraction.

Section 3 introduces the algorithms required to determine the measurement accuracy derivable from radar-based surveillance data. Section 4 addresses the 3-bit flight status (FS) field contained in each Mode S surveillance reply.

Section 5 discusses tests of the ELS aircraft identification function in Mode S transponder register 20_{16}[2]. Section 6 discusses ELS register 30_{16} ACAS Advisory, which must be tested under highly controlled conditions using special ACAS test equipment. ACAS tests should not be conducted with the aircraft in actual flight; see [9].

Section 7 presents tests of the five data fields in the EHS Selected Vertical Intention register (40_{16}). Section 8 discusses tests of the five data fields in the EHS Track and Turn register (50_{16}). Section 9 discusses tests of the five data fields in the EHS Heading and Speed register (60_{16}).

Appendix A of this report gives the Mode S transponder register definitions for each register used by the ELS and EHS validation processes. The register layouts in Appendix A have been extracted from [2]; in the event that the requirements are revised such that the register layouts have changed, the layouts presented in the latest version of that document take precedence.

Appendix B provides example horizontal tracker/smoother algorithms that may be used to compute horizontal velocity estimates from the sensor position data. Both real-time and non real-time tracker/smoother algorithms are described. Appendix C provides a vertical tracker/smoother that may be used to compute vertical rate estimates from altitude inputs in 100-foot flight levels. Appendix D provides a vertical tracker/smoother that may be used to compute vertical rate

[2] Throughout this report, Mode S transponder register designators (Comm-B Data Selectors or BDS codes) are given in hexadecimal notation with the subscript 16. Aircraft Mode 3/A identity codes are in octal notation with the subscript 8. All other numeric values are assumed to be in decimal notation, with no subscript. Bit numbering within a register is with respect to the start of the 56-bit Comm-B data (termed the MB field), with the left-most bit numbered 1. Bit positions are expressed in decimal.

estimates from altitude inputs in 25-foot flight levels (as provided by some Mode S-equipped aircraft). Appendix E provides a non real-time vertical tracker/smoother algorithm. Appendix F describes how to use values of ground speed and other surveillance inputs to validate airspeed values for EHS.

Appendix G describes the information potentially available in the Mode S GICB routine meteorological register (44_{16}). If the aircraft populates this register, then the winds and temperature data required to fully validate the airspeed and heading data of EHS can be extracted directly from the aircraft.

Appendix H describes the Mode S communications interface formats and protocols supporting the FAA's terminal sensors. These sensors (specified in [6]) do not support the ASTERIX input/output format – rather, they provide data as specified in [13] and [14]. Appendix H provides the techniques to use this interface for ELS/EHS validation. Appendix I describes the internationally standardized ASTERIX Category 018 interface used to support surveillance and data link communications functionality in sensors that do not provide the interface discussed in Appendix H.

Appendix J provides the complete derivation of the equations used to compute the Cartesian components of the surveillance radar measurement variance distribution that are given in Section 3.3. The Cartesian components are a function of the radar's range, azimuth, and altitude position measurement variance (system parameters) together with the target report's range, azimuth, and altitude. This appendix provides an example of the application of the master equation in Section 3.1.

1.3 Compliance Verification Methodology

The ELS/EHS compliance verification algorithms and procedures described in this report may be implemented as a real-time monitor or as a post-processing system operating on recorded data sets. Lincoln Laboratory has developed a post-processing version of the algorithms that is currently being used to validate compliance for aircraft in the coverage of two Mode S sensors. One of these sensors is a research asset operated by Lincoln Laboratory at Hanscom AFB in Lexington, MA and the other sensor is a research asset operated by the FAA's William J Hughes Technical Center in Atlantic City, NJ. Each sensor continuously detects the entry of new Mode S transponders into their airspaces, enrolls the new transponders, and extracts register data using standard Mode S protocols in the process of surveillance. Each sensor provides a flow of correlated aircraft surveillance and register data to a dedicated processor at MIT Lincoln Laboratory; those processors record the data (with time tags) in files for each day; new recording files are initiated at midnight (UTC).

The Lincoln Laboratory implementation of the ELS/EHS compliance verification data analysis is performed in a post-processing mode on a single file of recorded data, nominally once a day. The first processing step is to build a searchable database using the recorded data. The analysis can be performed on multiple days by processing multiple data files into the database. The data is keyed by the aircraft Mode S address so that the complete set of data associated with a specific aircraft's can be extracted for analysis. The transponder's datalink capability, and its assertions of ELS and EHS capability are determined as the database is built. In addition, the lists

of transponder register availability are determined for each aircraft. (Section 2 describes the analysis of transponder capability for ELS and EHS.)

Once the database is built, all data for the most recent flight for each aircraft of interest (in this case, state aircraft) are retrieved for further analysis. A smoothed path is computed based on the surveillance reports for the aircraft and used as the truth track referenced elsewhere in this report. The smoothed path is used to compute velocity estimates (both horizontal and vertical) for use in verifying the contents of the EHS registers. (Appendix B of this report describes the horizontal smoothing algorithms, while Appendices C and D describe the vertical smoothing algorithms.)

The next step in the compliance determination process is to step through the ELS/EHS register data associated with the aircraft source data for a given smoothed path. Each data item containing aircraft state data is examined to determine whether the reported data is consistent (within some tolerance) with its corresponding state derived from the truth track; the computation of the tolerances is described in Section 3, and the data item consistency checks for each ELS and EHS register are described in Sections 4 through 9.

Examination of a register's data items can be conducted even in the cases where the capability and status bits do not indicate availability of the register. This is possible in the case of a transponder whose configuration and status bits are not properly set, but whose applications are providing data to the ELS/EHS registers. The data tests described in the following sections are processed if the registers are available, even if the status bits do not indicate that availability.

The monitoring system maintains counts of consistency checks and failures. Once all individual data items have been examined, the percentage of positive results is computed and a compliance determination is made based on that percentage. Finally, an aircraft-specific compliance report is produced based on the results of the tests. This process is repeated for data associated with each Mode S address in the fleet of interest and fleet monitoring statistics are produced based on the collection of aircraft-specific compliance analyses.

1.4 Semantics of the Tests

The compliance determination tests in the following sections of this report include boxes containing colored text with specific test information and are arranged as follows:

Test nn:	**The statement of the test, with the test number indicated by "nn."**
Correct condition:	**Acceptable results of the test.**
Error condition:	**Test failure conditions.**

The **BLUE** text indicates which ELS or EHS element is being tested and how it is tested. The **GREEN** text indicates a positive test result and the **RED** text indicates the test failure. "Error condition:" indications in bold-red text are example messages that could be used in non-compliance reports to indicate the nature of test failures.

The Error Conditions include text messages to be generated by the monitoring system to assist in non-compliance resolution. An alert of non-compliance will contain one or more of these statements, one for each detectable failure. Whenever possible, the analysis continues even after a test has failed. In any event, a non-compliance report will indicate all detectable test failures.

It should be noted that some number of non-compliance alerts might be generated even for an aircraft that is generally compliant. These alerts could be caused by transient conditions in the avionics, irregularities in the surveillance data, etc. The recorded data would need further analysis to determine the causes of the alerts and whether they indicate anomalies in the testing procedures or if they point to actual system problems in the aircraft's Mode S avionics. One way to evaluate overall compliance is to compute the percentage of Mode S update scans that cause alerts to be generated over the length of each aircraft's track. While the exact maximum acceptable alert percentage value for an aircraft to be deemed compliant remains to be determined, it is likely to be of the order of 5 percent or less.

1.5 Surveillance Basics

Figure 1-3 illustrates the layout of fields in Mode S Surveillance interrogations and replies. The standard surveillance reply is a 56-bit data message; those replies do not deliver any Mode S register data. If the reply is in response to an altitude interrogation, then downlink format (DF) number 20 is used – if the reply is in response to an identity interrogation, then DF number 21 is used. The Mode S ELS and EHS applications use the 112-bit Comm-B reply format to transfer a 56-bit MB field with the extracted contents of a specified Mode S transponder register as part of the Mode S transponder's surveillance response.

In either surveillance reply format, the left-most 3 bits of the surveillance & communications control field contain the flight status (FS) and the right-most 13 bits contain either the aircraft's Mode C altitude or the aircraft's Mode 3/A identity code. The middle 11 bits of the surveillance and communications control field are composed of a 5-bit downlink request field and a 6-bit utility message field; those fields are not significant to this report and will not be further discussed. The address/parity field in each reply contains the aircraft's Mode S address and is used to perform error-detection and correction algorithms on the reply bits.

SURVEILLANCE INTERROGATION AND REPLY

FORMAT NO. (5 Bits)	SURV. & COMM. CONTROL (27 BITS)	ADDRESS/PARITY (24 BITS)	**56 BITS**

SURVEILLANCE/COMMUNICATION INTERROGATION AND REPLY - COMM-A AND COMM-B

FORMAT NO. (5 Bits)	SURV. & COMM. CONTROL (27 BITS)	MESSAGE FIELD (56 BITS)	ADDRESS/PARITY (24 BITS)	**112 BITS**

Figure 1-3. Mode S Surveillance/Communications Data Formats.

If the surveillance source provides ASTERIX Category 048 target reports (see [5]), then the 56 bits of extracted Mode S transponder register data are provided in the format of Data Item 250, illustrated in Figure 1-4. Since multiple registers can be extracted on a surveillance scan, the first 8 bits of the message contain a count of the registers represented in the ASTERIX message. Following the repetition count are one or more MB/BDS data blocks. Each data block contains the 56-bit extracted Mode S transponder register contents (MB field) followed by the 8-bit BDS code identifying the register.

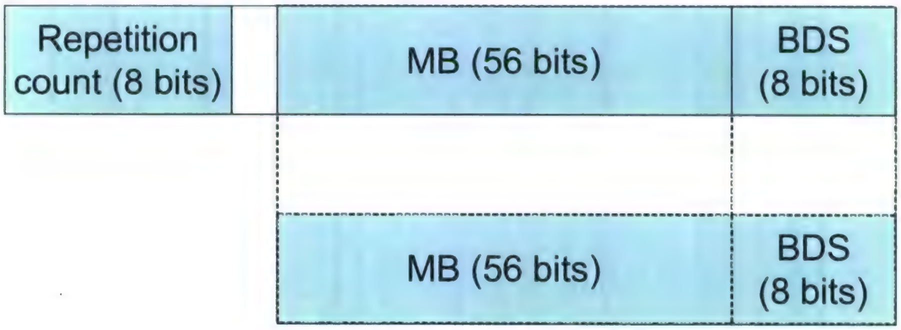


Figure 1-4. Format of ASTERIX Category 048 Data Item 250 (Mode S MB Data).

If the Comm B data was sent as a Mode S broadcast rather than a GICB extraction, then the BDS code will be zero. The first 8 bits of the MB field for a Mode S Comm B broadcast message contain the BDS code (e.g., registers 10_{16}, 20_{16}, and 30_{16}). Mode S transponder registers 20_{16} and 30_{16} have their own ASTERIX formats, so they would not be found in an ASTERIX Data Item 250 message.

Figure 1-5 illustrates the organization and basic data flows for the subset of the Mode S transponder registers used in the ELS and EHS applications. Color-coding is used to group the registers by application: ELS (yellow) and EHS (red). Registers shown in gray are indirectly involved with these applications, but are not directly called out by the application specification. The figure employs thick arrows to denote the transponder static and dynamic configuration data flows. Appendix A contains more readable versions of the register layouts in Figure 1-5.

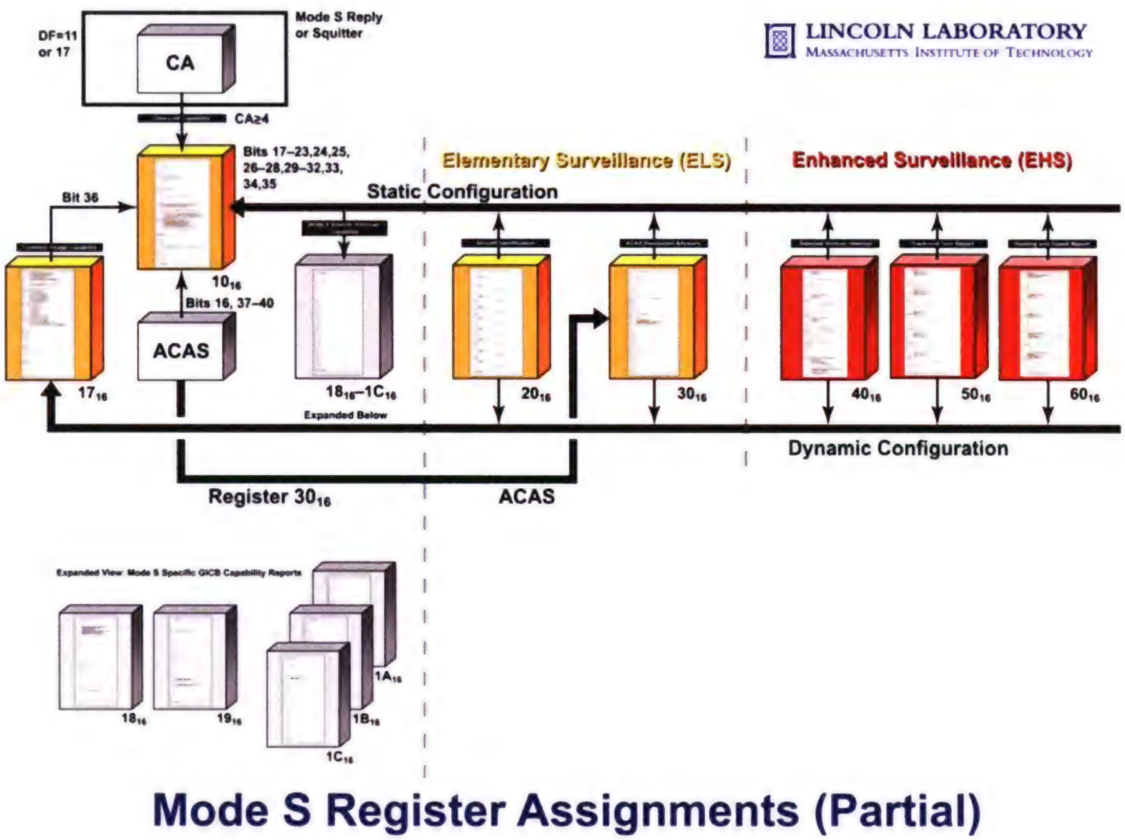


Figure 1-5. Mode S Register Architecture for ELS and EHS Data Link Applications.

2. CONFIGURATION VALIDATION

This section discusses the status and configuration bits that indicate the communication and ELS/EHS capability of the transponder. The transponder must successfully pass all of the tests described below to be deemed properly configured for ELS and EHS applications. Further, the transponder must pass each of the data item tests presented in Sections 4 though 9 in order to be deemed fully compliant with the ELS and EHS mandates.

There are a number of bits and fields in the Mode S transponder provided for avionics system configuration definition. Most of these are static – written once at avionics system initialization. The ELS/EHS validation procedures described in this report assume that these configuration values are examined once, in the order listed in this section. (If the configuration of the avionics changes in flight (e.g., equipment failures), then some of the tests may need to be repeated.) All the tests in this section must be passed in order for compliance verification to proceed with the further validation tests in subsequent Sections 4 through 9.

2.1 Capability (CA) Field Validation

The 3-bit transponder capability (CA) field is obtained from either the aircraft's Mode S All-Call Reply and Acquisition Squitter (DF=11) or the Extended Squitter (DF=17) downlink messages. The CA field occupies bits 6 through 8 in these messages, just after the 5-bit downlink format (DF) field. To indicate support for Mode S ELS and EHS applications, the CA field value must be greater than or equal to 4.

The transponder capability should be tested on acquisition of the aircraft by the surveillance sensor:

Test 01:	**Compare transponder CA field with the value 4.**
Correct condition:	**CA must be greater than or equal to 4.**
Error condition:	**Transponder capability (CA) value is less than 4; the transponder does not support Mode S data link applications.**

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the information that would be contained in the CA value is available in bits 14 through 16 (the COM field) of Data Item 230. A value in the COM field greater than or equal to 1 implies a CA value greater than 4.

2.2 Capability Register Validation

Bits in the Mode S Specific-Services GICB Capability registers of the Mode S transponder indicate whether the aircraft's avionics are configured to support specific individual transponder registers. Register 18_{16} (see A-3 for the complete definition of the contents of this register) contains bits for the configuration status of registers 01_{16} through 38_{16}, which includes all those registers involved with ELS. The register configuration bits are assigned sequentially starting

with the low-order bit in the register (bit 56). These bits represent the wired configuration of the avionics – they are static and need to be extracted only once for any given transponder.

Given that the transponder CA field test (Section 2.1) is passed, the contents of register 18_{16} should be extracted and the tests in this section performed once at the acquisition of the aircraft. The register contents should be extracted again[3] and these tests should be repeated if the avionics signal a change in airborne configuration via a broadcast of the new settings for the data link capability register (10_{16}).

For a Mode S transponder to support ELS, the following bits in capability register 18_{16} must be set to 1:

a) Bit 41 (refers to availability of register 10_{16}) must be set to 1;

Test 02:	**Compare bit 41 of register 18_{16} with the value 1.**
Correct condition:	**Bit 41 must equal 1.**
Error condition:	**Bit 41 of register 18_{16} (Static Configuration) is not set to 1, implying that ELS register 10_{16} is not available.**

b) Bit 34 (refers to availability of register 17_{16}) must be set to 1;

Test 03:	**Compare bit 34 of register 18_{16} with the value 1.**
Correct condition:	**Bit 34 must equal 1.**
Error condition:	**Bit 34 of register 18_{16} (Static Configuration) is not set to 1, implying that ELS register 17_{16} is not available.**

c) Bit 25 (refers to availability of register 20_{16}) must be set to 1; and

Test 04:	**Compare bit 25 of register 18_{16} with the value 1.**
Correct condition:	**Bit 25 must equal 1.**
Error condition:	**Bit 25 of register 18_{16} (Static Configuration) is not set to 1, implying that ELS register 20_{16} is not available.**

---

[3] In a monitoring environment where data analysis is based on recorded data from an autonomous radar, it is not possible to direct the radar to repeat a register extraction. In that case, the analysis should seek ahead in the data stream for subsequent extractions; if none are found, the tests cannot be repeated.

d) If the aircraft is equipped with a functioning ACAS unit that is configured to generate resolution advisories (RAs), then bit 9 (refers to availability of register 30_{16}) must be set to 1. Bits 16, 38, and 39 of the transponder Data Link Capability Report (register 10_{16} -- see Figure A-1) indicate the ACAS configuration of the aircraft's avionics. Bit 39 is set to 1 if the aircraft is ACAS equipped. Bit 16 is set to 1 if the ACAS is currently operational. Bit 36 is set to one if the ACAS is generating RAs as well as traffic advisories (TAs).

Test 05:	**If the aircraft is equipped with an operating ACAS unit capable of generating RAs, compare bit 9 of register 18_{16} with the value 1.**
Correct condition:	**Bit 9 must equal 1.**
Error condition:	**Bit 9 of register 18_{16} (Static Configuration) is not set to 1, implying that ELS register 30_{16} is not available for the output of ACAS RA data.**

The configuration bits for the EHS registers are found in transponder register 19_{16}. (See A-4 for the complete definition of the contents of this register). Given that the transponder CA field test (Section 2.1) is passed, the contents of register 19_{16} should be extracted and the tests in this section performed once at the acquisition of the aircraft. The register contents should be extracted again and these tests should be repeated if the avionics signal a change in airborne configuration via a broadcast of the new settings for the data link capability register (10_{16}).

For a Mode S transponder to support EHS, the following bits in capability register 19_{16} must be set to 1:

a) Bit 49 (refers to availability of register 40_{16}) must be set to 1;

Test 06:	**Compare bit 49 of register 19_{16} with the value 1.**
Correct condition:	**Bit 49 must equal 1.**
Error condition:	**Bit 49 of register 19_{16} (Static Configuration) is not set to 1, implying that EHS register 40_{16} is not available**

b) Bit 33 (refers to register 50_{16}) must be set to 1; and

Test 07:	**Compare bit 33 of register 19_{16} with the value 1.**
Correct condition:	**Bit 33 must equal 1.**
Error condition:	**Bit 33 of register 19_{16} (Static Configuration) is not set to 1, implying that EHS register 50_{16} is not available.**

c) Bit 17 (refers to register 60_{16}) must be set to 1.

Test 08:	**Compare bit 17 of register 19_{16} with the value 1.**
Correct condition:	**Bit 17 must equal 1.**
Error condition:	**Bit 17 of register 19_{16} (Static Configuration) not set to 1, implying that EHS register 60_{16} is not available.**

2.3 Common-Usage Register Validation

The Mode S common-usage transponder capability register (17_{16}) contains configuration bits that are set to indicate the actual operational status (dynamic) of the most commonly used registers, including all ELS and EHS registers. (See A-2 for the complete definition of the contents of this register). Given that the appropriate transponder configuration tests (Sections 2.1, 2.2-b) are passed, the contents of register 18_{16} should be extracted and the tests in this section performed once at the acquisition of the aircraft. The register contents should be extracted again and these tests should be repeated if the avionics signal a change in airborne configuration via a broadcast of the new settings for the data link capability register (10_{16}).

For a Mode S transponder to support ELS, bit 7 in register 17_{16} (corresponding to register 20_{16}) must be set to 1.

Test 09:	**Compare bit 7 of register 17_{16} with the value 1.**
Correct condition:	**Bit 7 must equal 1.**
Error condition:	**Bit 7 of register 17_{16} (Dynamic Configuration) is not set to 1, implying that ELS register 20_{16} is not currently available.**

The following additional configuration bits must be set to 1 in the common-usage capability register (17_{16}) to support EHS:

a) Bit 9 (refers to register 40_{16}) must be set to 1;

Test 10:	**Compare bit 9 of register 17_{16} with the value 1.**
Correct condition:	**Bit 9 must equal 1.**
Error condition:	**Bit 9 of register 17_{16} (Dynamic Configuration) not set to 1, implying that EHS register 40_{16} is not currently available.**

b) Bit 16 (refers to register 50_{16}) must be set to 1; and

Test 11:	**Compare bit 16 of register 17_{16} with the value 1.**
Correct condition:	**Bit 16 must equal 1.**
Error condition:	**Bit 16 of register 17_{16} (Dynamic Configuration) not set to 1, implying that EHS register 50_{16} is not currently available.**

c) Bit 24 (refers to register 60_{16}) must be set to 1.

Test 12:	**Compare bit 24 of register 17_{16} with the value 1.**
Correct condition:	**Bit 24 must equal 1.**
Error condition:	**Bit 24 of register 17_{16} (Dynamic Configuration) not set to 1, implying that EHS register 60_{16} is not currently available.**

2.4 Data Link Capability Register Validation

The Mode S transponder data link capability register (10_{16}) contains a number of avionics configuration and status fields. (See A-1 for the complete definition of the contents of this register.) Given that the appropriate transponder configuration tests (Sections 2.1, 2.2-a) are passed, the contents of register 18_{16} should be extracted and the tests in this section performed once at the acquisition of the aircraft. These tests should be repeated if the avionics signal a change in airborne configuration via a broadcast of the new settings for the data link capability register (10_{16}).

For a Mode S transponder to support ELS and EHS applications, the following conditions must all be true:

a) Bits 1 through 8 (BDS code) = 10_{16};

Test 13:	**Compare bits 1 through 8 of register 10_{16} with the value 10_{16}.**
Correct condition:	**Bits 1 through 8 must equal 10_{16}.**
Error condition:	**The value in bits 1-8 of ELS register 10_{16} is not set to 10_{16}; incorrect register identifier (BDS code).**

b) Transponders built under specifications prior to 2002 (sub-network Version 3) do not support ELS; transponders built under specifications released in 2002 (sub-network Version 3) or later (sub-network Version 4, Edition 1 in 2007) accommodate ELS. Bits 17 through 23 (sub-network version number) of register 10_{16} must be in the range 3...4;

Test 14:	**Compare bits 17 through 23 of register 10_{16} with the values 3 and 4.**
Correct condition:	**Bits 17 through 23 must equal 3 or 4.**
Error condition:	**The value in bits 17..23 (sub-network version number) of ELS register 10_{16} is not in range 3…4. Sub-network version number is incorrect.**

c) Bit 25 (Mode S-Specific Services Capability) must be set to 1, indicating that registers other than 02_{16}, 03_{16}, 04_{16}, 10_{16}, 17_{16}, $1C_{16}$, 20_{16}, and 30_{16} are available for down linking. A value of zero in that bit field means that registers 40_{16}, 50_{16}, and 60_{16} are not available for extraction;

Test 15:	**Compare bit 25 of register 10_{16} with the value 1.**
Correct condition:	**Bit 25 must equal 1.**
Error condition:	**Bit 25 of ELS register 10_{16} (Mode S Specific-Services Capability) is not set to 1.**

d) Bit 33 (Aircraft Identification Capability) must be set to 1 to indicate that the aircraft identification is being provided to the transponder; and

Test 16:	**Compare bit 33 of register 10_{16} with the value 1.**
Correct condition:	**Bit 33 must equal 1.**
Error condition:	**Bit 33 of ELS register 10_{16} (Aircraft identification capability) is not set to 1, indicating that the transponder cannot provide the flight identification.**

e) Bit 35 (Surveillance Identifier Code) must be set to 1.

Test 17:	**Compare bit 35 of register 10_{16} with the value 1.**
Correct condition:	**Bit 35 must equal 1.**
Error condition:	**Bit 35 of ELS register 10_{16} (Surveillance Identifier Code (SI) capability) is not set to 1, indicating that the transponder does not support SI codes.**

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the Mode S-Specific Services flag is available as bit 8 (MSSC fields) of Data Item 230. The aircraft identification capability flag is available as bit 6 (AIC field) of Data Item 230. As indicated in text associated with Figure 1-4, the contents of the extracted register 10_{16} are available in Data Item 250.

3. CALCULATION OF VALIDATION THRESHOLDS

This section provides the algorithms required to determine the measurement accuracy derivable from radar-based surveillance data. When radar-based surveillance data is used to validate Mode S EHS data values, these algorithms should be used to determine the accuracy thresholds to be employed for the validation comparisons for the respective data items. The algorithms described in this section calculate the data error distribution "sigma" – the standard deviation of the value expected for the particular variable. The validation thresholds would simply be a multiple of the calculated sigma for the variable. A multiplier value of 3 (denoted 'n' throughout this section) is typically employed, since data measurement errors in excess of three standard deviations are rare.

3.1 Assumptions

The equations used in this section were derived primarily from Section 10 of reference [4]. A simplifying assumption has been made that the sources of radar surveillance data use simple Kalman filters or tracker algorithms (e.g., 2-point interpolators or alpha-beta smoothers). This simplifying assumption holds true for Mode S and other current radar surveillance ground sensors. Two example horizontal path smoothing algorithms are described in Appendix B of this report, a retrospective (non-real-time) smoother appropriate for use in processing recorded data for post-flight analysis and a real-time algorithm appropriate for use in quick-look during flight testing.

The master equation for the computation of the various error distribution sigmas in this report is the following (10-23 from [4]) that defines how to convert the measurement variances for a function in one coordinate system into corresponding measurement variances for the function in another coordinate system. In the case of this report, the known variances are two-dimensional in range and azimuth for the Mode S ground surveillance sensor, but the variances in Cartesian x-y coordinates are desired. Variance terms (sigma squared) can be directly added as indicated in the master equation.

$$\sigma^2(f(x_1,\ldots,x_n)) = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}\sigma^2_{x_i x_j}$$

3.2 Inputs

The equations derived in this section assume that the sensor measurement errors in the range and azimuth directions are inputs given as parameters of the surveillance radar sensor – denoted as SigmaRange[4] and SigmaAzimuth, in nautical miles, and radians, respectively. For a typical US civilian Mode S sensor, the value of SigmaRange is 0.01 nautical miles and the value of SigmaAzimuth 0.001 radians. The values of these surveillance sensor parameters would be configuration inputs to the validation testing software.

---

[4] See Section 3.3 for a discussion of slant range and the computation of ground range.

For each surveillance target report correlated to a given aircraft track, the following input data items are assumed:

Range:	*slant* range (strict distance from the sensor), in nautical miles;
Azimuth:	in radians clockwise from true north;
Altitude:	in nautical miles (or feet), typically barometric; and
Time:	time (also interchangeably denoted T).

The aircraft track is assumed to maintain the previous values of the report data, as well as previous values of the data sigmas as calculated below. Also, it is assumed that the time difference (or number of scans) between the current and previous correlation reports for the track is known. (If required, the number of scans may be converted to time units using the system scan time parameter.)

If the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the range and azimuth values are available in Data Item 040. Range is 16 bits in units of 256ths of a nautical mile. Azimuth is 16 bits in units of 360/65536 degrees (about 0.0055 degree steps). Time is available in Data Item 140 as a 24-bit value. The time unit is 128ths of a second. The correlating track number is available in Data Item 161 in the range 0 to 4095. Altitude is available in Data Item 090 as a 14-bit value in units of 25 feet. The upper two bits of the 16-bit altitude data item are used to flag error conditions. The bits should both be zero when the altitude is usable.

3.3 Derived Intermediate Terms

Range Conversion: The Cartesian ground position values X and Y are derived from the measured range, azimuth, and altitude. The first calculation is to compute the *ground* range (the distance from the sensor to the spot on the earth directly below the aircraft) from the *slant* (or *measured*) range and altitude. Since the aircraft for which EHS is available will be Mode S-equipped, a measured altitude should be available and is used to convert slant range to ground range:

$$\text{Ground range} = (\text{Slant range}^2 - \text{Altitude}^2)^{0.5}$$

If altitude is generally available, altitudes missing from some reports can be substituted using an altitude smoother (see Appendix C, D, or E). If no altitude is available, use a default value of 0.5 nautical miles or ½ of the slant range, whichever is smaller.

Henceforth in this report *range* refers to *ground range* as computed above.

The horizontal tracker algorithms in Appendix B of this report contain calculations of the ground positions. Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the Cartesian coordinates may be available in optional Data Item 042. Each component value is 16 bits long in units of 128ths of a nautical mile.

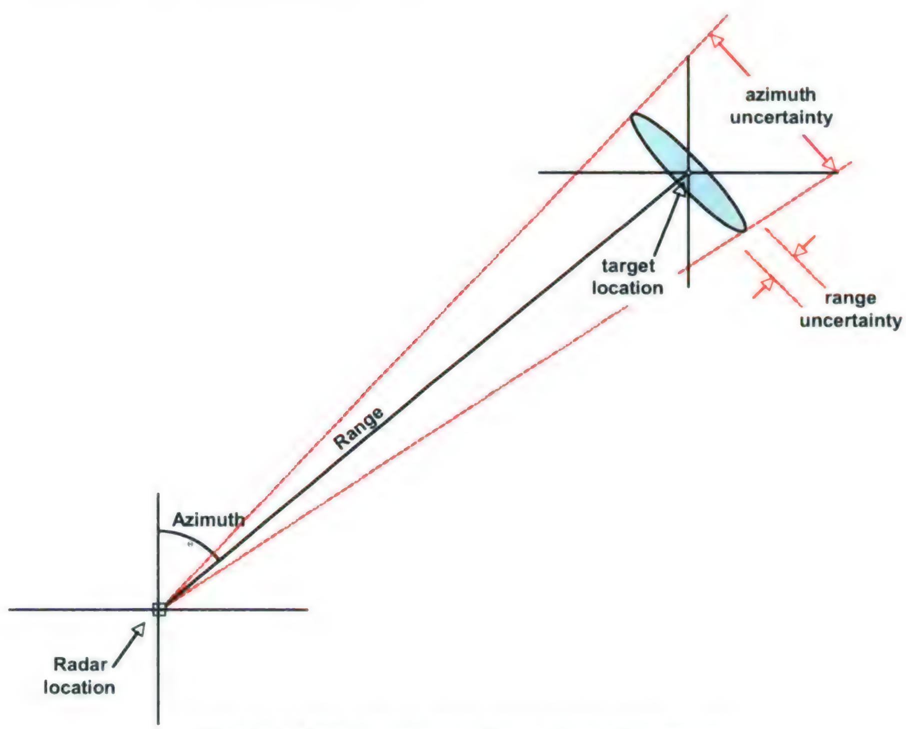
Coordinate Conversion: Derivation of the computations for the measurement variances in Cartesian x-y coordinates in this section uses the master equation from Section 3.1. Azimuth angle measurement uses the ATC convention (clockwise from north) and the ground range. Hence:

X = Range * sin(Azimuth); and

Y = Range * cos(Azimuth).

The measurements of range and azimuth are assumed to be independent, so there are no non-zero cross-terms in range/azimuth. The variances in the Cartesian coordinate system are dependent (e.g., a variance in azimuth may impact the variance in both x and y), so there is a variance cross-term in x-y.

This dependency in the Cartesian coordinate variances is illustrated in the top-down view of Figure 3-1. An aircraft is measured to be at a given range and azimuth from a ground radar sensor. The shaded ellipse illustrates the distribution of possible aircraft positions (given standard radar errors in range and/or azimuth measurement). For example, consider a Mode S sensor whose range error sigma is about 0.01 nautical miles (about 60 feet) and whose azimuth error sigma is 0.001 radians. At a range of 50 nautical miles, the size of the error ellipse in the azimuth direction is about 300 feet. Note that if the range measurement error is positive, the error in both x and y must be positive – if the range error is negative then the error in both x and y must be negative (the errors in x and y are dependent). Similarly, an increase in the azimuth measurement implies an increase in x and a decrease in y, etc.



(this is a plan view as seen from above the sensor)

Figure 3-1. Relationship Between Ground Range/Azimuth and Cartesian X-Y Variances.

The following equations are used to calculate the values of the squares of the positional error sigma values in units of nautical miles-squared. (As was mentioned in Section 3.1, variances (sigma-squared terms) are calculated so that they can be directly added.) Denoted SigmaX and SigmaY, these are the positional error sigma values in Cartesian coordinates. There is also a cross-term square (also in units of nautical miles-squared), SigmaXY^2, that will be used in the later calculations of SigmaHeading and SigmaSpeed. Only the radar surveillance range and azimuth measurement inputs are used in these equations. (See Appendix J for the complete derivation of these equations.)

$$\text{SigmaX}^2 = (\text{SigmaRange}^2 * \sin(\text{Azimuth})^2) + (\text{Range}^2 * \text{SigmaAzimuth}^2 * \cos(\text{Azimuth})^2)$$

$$\text{SigmaY}^2 = (\text{SigmaRange}^2 * \cos(\text{Azimuth})^2) + (\text{Range}^2 * \text{SigmaAzimuth}^2 * \sin(\text{Azimuth})^2)$$

$$\text{SigmaXY}^2 = [\text{SigmaRange}^2 - (\text{Range}^2 * \text{SigmaAzimuth}^2)] * \sin(\text{Azimuth}) * \cos(\text{Azimuth})$$

Note: the SigmaXY^2 term indicates the correlation between error in the X-direction with error in the Y-direction. It may be either positive or negative, depending on the measured azimuth of the aircraft. The square root of the SigmaXY^2 term is not required in any further calculations, so SigmaXY^2 being negative is not a problem.

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [4]), then the Cartesian X and Y sigma values may be available in optional Data Item 210. Each component is 8 bits long in units of 128ths of a nautical mile.

3.4 Calculating Heading Sigma

The derivation of the computations for the heading variance in this section uses the master equation from Section 3.1. Heading is defined based on the two most-recent measurements in Cartesian coordinates as follows (this is 10-31 from [3]):

$$Heading = \tan^{-1}\left(\frac{x_{current} - x_{previous}}{y_{current} - y_{previous}}\right)$$

employing ATC conventions for angular measurement (i.e., clockwise from north). Aircraft altitude is assumed to be slowly varying, so that the impact of altitude changes on horizontal position can be ignored in the calculations of heading (which typically works on the time scale of one sensor scan).

The equation for $\text{Sigma}_{\text{Heading}}$ assumes that there are values for the current Cartesian x-y position as well as the current SigmaX, SigmaY values, and the cross-term SigmaXY value as calculated in Section 3.3. These values are denoted with the subscript *current*. Similarly, it is assumed that there are saved values for Cartesian x-y position and sigma values for the previous measurement data point -- denoted with the subscript *previous*. If there is only one data report available for a given aircraft track, then the heading error sigma value for this track cannot be calculated and should default to 0.

The following equations generate intermediate terms for the heading error sigma calculation:

$$\text{DeltaX} = (X_{current} - X_{previous})$$

$$\text{DeltaY} = (Y_{current} - Y_{previous})$$

$$\text{TermX} = \text{DeltaX}^2 * (\text{SigmaY}^2_{previous} + \text{SigmaY}^2_{current})$$

$$\text{TermY} = \text{DeltaY}^2 * (\text{SigmaX}^2_{previous} + \text{SigmaX}^2_{current})$$

$$\text{TermXY} = 2 * \text{DeltaX} * \text{DeltaY} * (\text{SigmaXY}^2_{previous} + \text{SigmaXY}^2_{current})$$

$$\text{Denom} = (\text{DeltaX}^2 + \text{DeltaY}^2)^2$$

The following equation yields the heading error sigma value squared in units of radians-squared based on the intermediate values calculated above. Note that there must be a protection in the algorithm against a denominator value of zero (e.g., a non-moving aircraft track). The sigma heading error value should be defaulted to infinity for this degenerate case. No heading validation tests can be performed in this default case.

$$\text{Sigma}_{Heading}{}^2 = (\text{TermX} + \text{TermY} - \text{TermXY}) / \text{Denom}$$

$\text{Sigma}_{Heading}$ can be prepared for use in checking reported heading by taking the square root and converting to degrees (multiplying by $180/\pi$). Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [4]), then the heading sigma value may be available in optional Data Item 210. The heading sigma value is 8 bits long and given in 360/4096 (about 0.088) degree steps.

3.5 Calculating Ground Speed Sigma

The derivation of the computations for the speed variance in this section uses the master equation from Section 3. Speed is defined based on the most-recent two measurements in Cartesian coordinates as follows:

$$Speed = \frac{\sqrt{(x_{current} - x_{previous})^2 + (y_{current} - y_{previous})^2}}{(Time_{current} - Time_{previous})}$$

Aircraft altitude is assumed to be slowly varying, so that the impact of altitude changes on horizontal position can be ignored in the calculations of speed (which typically work on the time scale of one sensor scan). The time values are assumed to be completely independent of the position measurements, so only the position variances come into play. (This equation for speed is a simplified version of 10-34 in [3]. It assumes that aircraft maneuvers (a non-zero turn rate) are taken into account by a position tracker such as that described in Appendix B of this report.)

The calculation for Sigma_{Speed} makes the same assumptions on inputs as the calculation for $\text{Sigma}_{Heading}$ in Section 3.4. The intermediate values DeltaX and DeltaY are carried over. The positional error sigma values are carried over from Section 3.3. The following equations derive

intermediate values for the calculation of the square of the sigma error for ground speed. DeltaTime may be computed directly (if report time tags are available) or indirectly from the scan count difference and the radar sensor's scan period parameter. If there is only one data report available for an aircraft track, then the speed sigma value for the track cannot be calculated and should default to 0.

$$\text{DeltaTime} = T_{current} - T_{previous}$$

$$\text{Denom} = (\text{DeltaX}^2 + \text{DeltaY}^2) * \text{DeltaTime}^2$$

$$\text{TermX}_{current} = (\text{DeltaX}^2 * \text{SigmaX}^2_{current})$$

$$\text{TermX}_{previous} = (\text{DeltaX}^2 * \text{SigmaX}^2_{previous})$$

$$\text{TermY}_{current} = (\text{DeltaY}^2 * \text{SigmaY}^2_{current})$$

$$\text{TermY}_{previous} = (\text{DeltaY}^2 * \text{SigmaY}^2_{previous})$$

$$\text{TermXY}_{current} = (2 * \text{DeltaX} * \text{DeltaY} * \text{SigmaXY}^2_{current})$$

$$\text{TermXY}_{previous} = (2 * \text{DeltaX} * \text{DeltaY} * \text{SigmaXY}^2_{previous})$$

$$\text{Term}_{current} = \text{TermX}_{current} + \text{TermY}_{current} + \text{TermXY}_{current}$$

$$\text{Term}_{previous} = \text{TermX}_{previous} + \text{TermY}_{previous} + \text{TermXY}_{previous}$$

The following equation gives the square of the ground speed error sigma value (in units of nautical miles per time unit - squared). Note that there must be a protection against a denominator value of zero (a non-moving track). Set the ground speed error sigma speed value to infinity for this case. No speed validation tests can be performed in this default case.

$$\text{Sigma}_{Speed}^2 = (\text{Term}_{current} + \text{Term}_{previous}) / \text{Denom}.$$

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [4]), then the speed sigma value may be available in optional Data Item 210. The heading sigma value is 8 bits long and given in steps of (2^{-14}) nautical miles per second (about 0.22 knots).

3.6 Calculating Heading-Rate Sigma

Heading rate is defined by the following equation (assuming no change in turn rate over the measurement time). The value of heading from the current measurement and the saved heading from a previous measurement are assumed. If there is only one data report available for an aircraft track, then the heading rate sigma value for the track cannot be calculated and should default to 0.

$$\text{HeadingRate} = (\text{Heading}_{current} - \text{Heading}_{previous}) / \text{DeltaTime}$$

'DeltaTime' is the same value used in the calculation of ground speed in Section 3.5. The assumption of no turning acceleration is reasonable for short time periods and typical aircraft maneuvers. (The horizontal tracker algorithm described in Appendix B of this report uses a turn detector step to account for aircraft accelerations.) The heading error sigma for each heading measurement is assumed to be available as described in Section 3.4. Assuming that the heading error sigma values are independent, the square of the error sigma for heading rate may be given simply as:

$$\mathrm{Sigma}_{HeadingRate}^{2} = 2*(\mathrm{SigmaHeading}_{current} * \mathrm{SigmaHeading}_{previous}) / \mathrm{DeltaTime}^{2}$$

3.7 Calculating Roll-Angle Thresholds

Assuming that the aircraft is in a level and uniform turn, the relationship between roll angle 'ø' and the aircraft's true airspeed 'V' and turn rate 'w' is given by:

$$\phi = \tan^{-1}\left(\frac{V * w}{g}\right)$$

where 'g' is the standard acceleration due to gravity. The aircraft's turn rate 'w' is obtained from the validated track angle rate as described in Section 8.4 (converted to radians per unit time). The aircraft's true airspeed (validation described in Section 8.5) cannot be validated directly, since it is affected by local winds. The aircraft's ground speed, however, can be validated (as described in Section 8.3). Given that the ground speed has been validated, the true airspeed data will be assumed as valid here. Hence, given that ground speed, true airspeed, and track angle rate values are available, and the ground speed and track angle rate have been validated, the roll angle can be validated. If the required data fields are not available or their validation fails, then no further validation of roll angle (other than the basic "right turn equals right roll" test) can be performed.

The thresholds for passing the roll angle validation test may be computed from the validation error sigmas derived for speed (Section 3.5) and heading rate (Section 3.6). Denoting the speed sigma Sigma_{speed} and the heading rate sigma $\mathrm{Sigma}_{\,Heading\text{-}Rate}$, then the testing thresholds for roll angle ø are given by:

$$\phi_{\max} = \tan^{-1}\left(\frac{(V + n * Sigma_{Speed}) * (w + n * Sigma_{Heading-Rate})}{g}\right)$$

$$\phi_{\min} = \tan^{-1}\left(\frac{(V - n * Sigma_{Speed}) * (w - n * Sigma_{Heading-Rate})}{g}\right)$$

where 'n' denotes the number of sigma data errors acceptable for validation.

3.8 Calculating Altitude Rate Thresholds

Aircraft may (depending on their avionics) report their barometrically derived altitude in 100-foot quantization (termed flight levels) or they may report altitude in 25-foot units. Ground sensors (including Mode S) using the Common Digitizer (CD-2) output format output all aircraft

altitudes in flight levels – the altitudes for aircraft reporting 25-foot increments are rounded to the nearest flight level. Ground sensors using the ASTERIX output format can provide the 25-foot data from those aircraft that are capable of providing it.

Altitude rate is derived from the surveillance data using a tracker algorithm. Appendix C of this report describes an algorithm derived from the Mode S Traffic Information Service (TIS) application suitable for 100-foot flight level data, while Appendix D describes an algorithm derived from the ACAS application to be used with 25-foot data. Appendix E describes a non-real-time vertical tracker algorithm suitable for processing recorded data.

The threshold for passing the altitude rate test may be approximated by dividing the altitude quantization by the time between altitude measurements. For 100-foot quantization and the approximately 5-second update period of a Mode S terminal sensor, this yields 1200 feet/minute as an upper bound on altitude rate indeterminacy. (Note: ACAS and TIS use the value 500 feet/minute as the threshold for level flight.) For purposes of data validation, a testing threshold of 1000 feet/minute would be appropriate for altitudes quantized to 100 feet. If 25-foot altitude data is available (e.g., output from a surveillance sensor supporting ASTERIX output), a testing threshold of 250 feet/minute would be appropriate.

4. FLIGHT STATUS (FS) VALIDATION

The 3-bit flight status (FS) field is contained in each Mode S surveillance reply. Flight Status includes three types of information:

Indication of whether the aircraft is airborne or on the ground;

Presence of a Mode 3/A code alert condition; and

The special position indicator (SPI).

A Mode 3/A alert condition indicates that the aircraft's Mode 3/A code has changed. There are two types of Mode 3/A code alerts: permanent and temporary. A permanent alert is a form of emergency declaration – the aircraft's Mode 3/A code has been changed to 7700_8, 7600_8, or 7500_8. Any other Mode 3/A code change is classed as a temporary alert indicating that the Mode 3/A code has been changed to a non-emergency value. The alert and SPI conditions are maintained for 18 seconds after they occur.

The FS encoding is defined in the following table.

Table 4-1
Surveillance Status Codes and Definitions

FS Code	Flight Status Condition
0	Airborne, No alert, No SPI
1	On the ground, No alert, No SPI
2	Airborne, Alert, No SPI
3	On the ground, Alert, No SPI
4	Ground or Airborne, Alert, SPI
5	Ground or Airborne, No Alert, SPI
6,7	Reserved

The alert portion of FS can be validated by comparison of the Mode 3/A code received from sensor surveillance against the extracted FS value. Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the Mode 3/A code is available in Data Item 070 and the FS value is available in bits 11 through 13 (the STAT field) of Data Item 230.

Test 18:	**Check the aircraft's Mode 3/A code for a change in the last 18 seconds. A code change indicates an alert condition.**
Correct condition:	**If a code change, then FS value must be 2, 3, or 4. If no code change, then FS value must be 0, 1, or 5.**
Error condition:	**ELS Flight Status Data Mode 3/A alert invalid; the FS code indicates alert but the Mode 3/A code has not changed.**

Validation of the airborne/on-the-ground portion of FS may be performed using a source of ground speed (this may be smoothed/tracked surveillance positional data such as described in Appendix B) and the aircraft altitude data. Since the source of altitude data from the aircraft is barometric (i.e., subject to variation due to local meteorological conditions) and may have only 100-foot quantization, it is not possible to make a fine-grained determination of whether the aircraft is on the ground or not simply by means of the altitude data. A source of topographic elevation data over the sensor coverage can be used to refine the airborne/on-ground decision, but it will still not be clearly defined. Also, an aircraft may appear to be flying slowly because it is in a strong headwind, not because it is taxiing on the ground. Hence, there will be cases where it is not possible to reliably differentiate airborne from on the ground with just the available sensor surveillance data.

If the aircraft's ground speed is greater than 100 knots or its altitude has increased more than 200 feet to its current value, then the aircraft has become airborne. Note: if the current speed determination variance for the aircraft (see Section 3.5) is greater than 30 knots, then the ground speed test cannot be applied here.

Test 19:	**Check the aircraft's ground speed and altitude change. If the speed is greater than 100 knots (with a variance of less than 30 knots) or the altitude has increased more than 200 feet up to its current value, then the FS should indicate airborne.**
Correct condition:	**If the ground speed and altitude change indicate airborne, then the FS value must be 0, 2, 4 or 5. Otherwise, the FS value must be 1, 3, 4, or 5.**
Error condition:	**ELS Flight Status Data indicates on-ground when the state data (ground speed and altitude change) indicate that the aircraft is actually airborne.**

If the aircraft's ground speed is less than 50 knots and its altitude has not increased by at least 100 feet to its current value, then the aircraft is declared to be on the ground. Note: if the current speed determination variance for the aircraft (see Section 3.5) is greater than 30 knots, then the ground speed test cannot be applied here.

Test 20:	**Check the aircraft's ground speed and altitude change. If the speed is less than 50 knots (with a variance of less than 30 knots) and the altitude has not increased more than 100 feet up to its current value, then the FS should indicate on the ground.**
Correct condition:	**If the ground speed and altitude change indicate on the ground, then the FS value must be 1, 3, 4, or 5. Otherwise, the FS value must be 0, 2, 4, or 5.**
Error condition:	**ELS Flight Status Data indicates airborne when the state data (ground speed and altitude change) indicate that the aircraft is actually on the ground.**

If a topographical database of ground elevation with resolution of at least one square mile over the sensor's coverage region is available, then the actual height of the aircraft above ground level can be computed (subject to barometric variations).

Test 21:	**If a source of ground elevation for the aircraft's position is known, compare the aircraft's reported altitude (barometric) against the ground elevation. If the altitude is more than 500 feet above the ground elevation, then the FS should indicate airborne.**
Correct condition:	**If the ground elevation data and altitude indicate airborne, then the FS value must be 0, 2, 4, or 5. Otherwise, the FS value must be 1, 3, 4, or 5.**
Error condition:	**ELS Flight Status Data indicates on-ground when the state data (ground elevation and altitude) indicate that the aircraft is actually airborne.**

Validation of the SPI bit portion of FS may be performed by comparison directly against the SPI value obtained through surveillance. Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the SPI bit is available in Data Item 020 as bit 3 of the first byte.

Test 22:	**Check the aircraft's SPI code bit against the FS value.**
Correct condition:	**If the aircraft's SPI bit is set, then the FS value must be 4 or 5. If the SPI bit is not set, then the FS value must be 0, 1, 2, or 3.**
Error condition:	**ELS Flight Status Data indicates a different SPI value from that derived from aircraft state data.**

5. AIRCRAFT IDENTIFICATION (REGISTER 20_{16}) VALIDATION

Mode S transponder register 20_{16} supports the aircraft identification function for ELS. (See A-5 for the complete definition of the contents of this register.) Given that the appropriate transponder configuration tests (Sections 2.1, 2.2-c, 2.3, and 2.4) are passed, the contents of register 20_{16} should be extracted and the tests in this section performed once at the acquisition of the aircraft. The register should be extracted again and these tests should be repeated if the avionics signal a change in airborne configuration via a broadcast of the new settings for the data link capability register (10_{16}). If the register data is already available (e.g., in a recorded data set), then the tests in this section should be performed even if the configuration data does not indicate its support.

Bits 1 through 8 of the register must hold the BDS code value 20_{16}. Note: the BDS code is obtained from the sensor interface (see Appendices G and H) – it should be duplicated in the high-order 8 bits of the register contents. If the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the 6-character aircraft identification data is available in the 48 bits of Data Item 240. This data item employs the character encoding of Table 5-1.

Test 23:	**Compare bits 1 through 8 of register 20_{16} with the value 20_{16}.**
Correct condition:	**Bits 1 through 8 must equal 20_{16}.**
Error condition:	**The value in bits 1-8 of ELS register 20_{16} is not set to 20_{16}; incorrect register identification (BDS code)**

The remaining 48 bits of the register form a string of eight characters. Character 1 is in bits 9 through 14, while character 8 is in bits 51 through 56. The character encoding value must obey the following rules:

Table 5-1
Value Ranges for Flight Identification

Values	Character Type
1-26	(letters A...Z)
32	(space)
48-57	(digits 0...9)

No other character value (0, 27…31, 33...47, or 58...63) is legal in the aircraft identification string in register 20_{16}.

Test 24: **Extract the 6-bit character coding value for each of the 8 characters in register 20_{16}. Check each character against the valid entries in Table 5-1.**

Correct condition: **Each 6-bit character coding in register 20_{16} is valid (as defined in Table 5-1).**

Error condition: **Invalid flight identification encoding in ELS register 20_{16}. Invalid character value(s) in the aircraft identification string.**

The character string must be left justified with no intervening spaces (encoding 32). Any unused characters at the end of the string must be set to spaces (encoding 32).

Test 25: **Extract the 6-bit character coding value for each of the 8 characters in register 20_{16}. Check that any space characters (coding=32) are at the end of the character string for padding.**

Correct condition: **All space characters (coding=32) lie at the right end of the character string for padding.**

Error condition: **Invalid flight identification encoding in ELS register 20_{16}. Invalid use of space characters in the aircraft identification string.**

The reference aircraft identification data is not obtainable from the sensor data, but can be obtained from the FAA as flight plan data, from the flight dispatcher, or from the pilot (possibly by voice). If the flight identification text string is available from an external source (e.g., the aircraft's flight plan), then the decoded text string from register 20_{16} must match it exactly.

Test 26: **If the aircraft's flight identification string is available (from flight plan or alternate source), compare it to the character string in register 20_{16}.**

Correct condition: **Aircraft identification string from alternative input source must match string in register 20_{16} character-for-character.**

Error condition: **Flight Identification data in ELS register 20_{16} does not match flight identification in submitted flight plan.**

6. ACAS ADVISORY (REGISTER 30_{16}) VALIDATION

Mode S transponder register 30_{16} is used to report resolution advisory (RA) data from an onboard ACAS unit. (See A-6 for the definition of the contents of this register. References [3] and [9] provide additional details of the coding used in this register.) Support for this register is required if the aircraft is equipped with an operating ACAS unit that is configured for RA generation. Bits 16, 38, and 39 of the aircraft's Data Link Capability register (10_{16} – see Figure A-1) indicate the configuration of the ACAS unit. If any of these bits are not set to 1, then no ACAS advisory register validation should be performed. If the register data is already available (e.g., in a recorded data set), then the tests in this section should be performed even if the configuration data does not indicate its support.

The contents of the ACAS advisory register may not be loaded by the avionics until an RA event occurs. Until this happens, the contents of the register should remain cleared to all zero. After the initial load of register 30_{16}, the BDS code value in the first 8 bits will be retained. For ELS compliance (once the register has been loaded the first time), bits 1 through 8 (BDS code) must contain the value 30_{16}. Note: the BDS code is obtained from the sensor interface (see Appendices G and H) -- it should be duplicated in the high-order 8 bits of the register contents.

Test 27:	**If the aircraft indicates that an operational ACAS unit configured for RA generation is onboard (bits 16, 38, and 39 of Data Link Capability (register 10_{16}) all set to 1), then compare bits 1 through 8 of register 30_{16} with the value 30_{16}.**
Correct condition:	**If all 56 bits of register 30_{16} are not zero (indicating that the register has been loaded at least once), then bits 1 through 8 in register 30_{16} must equal 30_{16}.**
Error condition:	**The value in bits 1-8 of ELS register 30_{16} is not set to 30_{16}; incorrect register identifier (BDS code).**

Full testing of ACAS is beyond the scope of this report. (See [9] for the complete test procedure definition for ACAS avionics.) Further validation of the contents of this register is not directly possible with the surveillance data from a ground sensor. While it might be possible to use the surveillance tracks generated to drive a simulation of the ACAS algorithms, the slower update rates of the ground surveillance data (every 5-12 seconds as opposed to the ACAS 1-second update) would make it difficult to ensure that the simulation was exact. Validation of the operation of an ACAS unit would normally be tested using a dedicated ground test unit capable of generating appropriate waveforms at 1030 and 1090 MHz to fully exercise the ACAS avionics.

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the ACAS resolution advisory data is available in the 56 bits of Data Item 260. This resolution advisory was generated during the previous scan.

7. SELECTED VERTICAL INTENTION (REGISTER 40_{16}) VALIDATION

If the avionics configuration tests (see Section 2) indicate that register 40_{16} (Mode S selected vertical intention) is supported by the aircraft, the contents of the register should be extracted. (See A-7 for the definition and contents of this register. References [2] and [3] provide additional details of the coding used in this register.) Since this data changes infrequently, register 40_{16} should be extracted at a low sampling rate (once per major track segment, if that can be determined) and the tests described in this section should be performed to validate the extracted register contents. If the configuration data does not indicate avionics support for the Mode S selected vertical intention transponder register (40_{16}), the register should not be extracted and the tests in this section should not be performed. If the register data is already available (e.g., in a recorded data set), then the tests in this section should be performed even if the configuration data does not indicate its support.

The Mode S selected vertical intention transponder register (40_{16}) contains five binary data fields. Each data field starts with a status bit indicating whether that data field contains valid information. At least one of the status bits (bit 1, 14, 27, 48, or 54) must be set in order to provide for EHS support.

Test 28:	**Examine status bits 1, 14, 27, 48, and 54 in register 40_{16}. At least one of the bits must be non-zero.**
Correct condition:	**At least one of the status bits 1, 14, 27, 48, or 54 in register 40_{16} must be non-zero.**
Error condition:	**All data field status bits in EHS register 40_{16} cleared to 0. No valid data in the register.**

Bits 40 through 47 and 52 through 53 are reserved and should be cleared to zero.

Test 29:	**Examine reserved bits 40..47 and 52..53 in register 40_{16}. All of these bits must be zero.**
Correct condition:	**Bits 40…47 and 52...53 in register 40_{16} must all be zero.**
Error condition:	**Reserved bits in EHS register 40_{16} are not cleared to zero; invalid register contents.**

If the status bit for a data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Test 30:	**Examine status bits 1, 14, 27, 48, and 54 in register 40_{16}. If any status bit is zero, then its corresponding data bits must also be zero.**
Correct condition:	**(a) If bit 1 is zero, then bits 2...13 must be zero.**
	(b) If bit 14 is zero, then bits 15...26 must be zero.
	(c) If bit 27 is zero, then bits 28…39 must be zero.
	(d) If bit 48 is zero, then bits 49...51 must be zero.
	(e) If bit 54 is zero, then bits 55...56 must be zero.
Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 40_{16}; invalid register contents.**

Since the data fields in this register are functions of the settings for the aircraft's FMS and/or MCP, they cannot be validated further from surveillance data. Specific ground and flight tests are required (including the ability to coordinate between the pilot and the test controller) to exercise this register.

If the status bit for MCP/FCU selected altitude (bit 1) is set, then the selected altitude in feet (0...65,520) may be extracted as follows:

(1) Extract bits 2 through 13 as VAL

(2) MCP/FCU selected altitude (feet) = 16 * VAL

The LSB of this field is 16 feet. This altitude may be derived from the aircraft's mode control panel (MCP), flight control unit (FCU), flight management system (FMS), altitude alerting device, or equivalent pilot input. Bits 54 through 56 indicate the source of the selected altitude in the avionics. Bit 54 is the status bit for the altitude source field. Bits 55 and 56 encode the altitude source as indicated in Table 7-1.

Table 7-1
Encoding of Target Altitude Source in Register 40_{16}

Encoding (bits 55,56)	Description
00	Unknown
01	Aircraft altitude
10	FCU/MCP selected altitude
11	FMS selected altitude

The data in the MCP/FCU selected altitude field (and the corresponding altitude source bits) could be validated by having the pilot enter specific test values into the appropriate cockpit inputs on command (could be done on the ground or in the air).

If the status bit for FMS selected altitude (bit 14) is set, then the selected altitude in feet (0…65,520) may be extracted as follows:

(1) Extract bits 15 through 26 as VAL

(2) FMS selected altitude (feet) = VAL * 16

The LSB of this field is 16 feet. The data is this field is derived from the flight management system (or equivalent input) managing the vertical profile of the aircraft. The data in the FMS selected altitude could be validated by having the pilot enter specific test values into the appropriate cockpit inputs on command (could be done on the ground or in the air).

If the status bit for barometric pressure setting (bit 27) is set, then the pressure setting in millibars may be extracted as follows:

(1) Extract bits 28 through 39 as VAL

(2) Barometric pressure setting (millibars) = (VAL / 10) + 800

The LSB for the barometric pressure setting is 0.1 millibars. If the actual setting is less than 800 mb or greater than 1209.5 mb, then the status bit for this field should be zero to indicate invalid data and the data field should be cleared to zero. The data in the barometric pressure setting could be validated by having the pilot enter specific test values into the appropriate cockpit inputs on command (this could be done on the ground or in the air).

If the status bit for the MCP/FCU mode bit field (bit 48) is set, then bits 49 through 51 indicate the current setting of particular altitude modes in the aircraft. If a particular bit is set, this indicates that the mode is currently active. Bit 49 indicates the vertical navigation mode, bit 50 indicates the altitude-hold mode, and bit 51 indicates the approach mode. The data in these bits could be validated by having the pilot enter specific test values into the appropriate cockpit inputs on command (could be done on the ground or in the air).

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the contents of the extracted register 40_{16} are available in Data Item 250 as described in Figure 1-2.

8. TRACK AND TURN (REGISTER 50_{16}) VALIDATION

If the avionics configuration tests (see Section 2) indicate that register 50_{16} (Mode S track and turn report) is supported by the aircraft, the contents of the register should be extracted on each scan of the surveillance sensor and the tests in this section should be performed to validate the extracted register contents. The register should not be extracted and the tests in this section should not be performed if the configuration data does not indicate support for the Mode S track and turn transponder register (50_{16}). If the register data is already available (e.g., in a recorded data set), then the tests in this section should be performed even if the configuration data does not indicate its support.

As noted in Section 1.3, an error condition for the contents of this register may be observed occasionally due to anomalous surveillance tracking or other causes. The percentage of register 50_{16} extractions that generate error alerts should be computed for each aircraft track. While the appropriate threshold value for this percentage to indicate EHS non-compliance is yet to be determined, it is likely to be less than 5 percent.

The Mode S track and turn transponder register (50_{16}) contains five binary data fields. (See A-8 for the complete definition of the contents of this register.) Each data field starts with a status bit indicating whether that data field contains valid information. At least one of the status bits (bit 1, 12, 24, 35, or 46) must be set to 1 in order to provide for EHS support.

Test 31:	**Examine status bits 1, 12, 24, 35, and 46 in register 50_{16}. At least one of the bits must be non-zero.**
Correct condition:	**At least one of the status bits 1, 12, 24, 35, or 46 in register 50_{16} must be non-zero.**
Error condition:	**All data field status bits in EHS register 50_{16} cleared to 0. No valid data in the register.**

If the status bit for a particular data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Test 32:	**Examine status bits 1, 12, 24, 35, and 46 in register 50_{16}. If any status bit is zero, then its corresponding data bits must also be zero.**
Correct condition:	**(a) If bit 1 is zero, then bits 2...11 must be zero.**
	(b) If bit 12 is zero, then bits 13...23 must be zero.
	(c) If bit 24 is zero, then bits 25…34 must be zero.
	(d) If bit 35 is zero, then bits 36...45 must be zero.
	(e) If bit 46 is zero, then bits 47...56 must be zero.
Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 50_{16}; invalid register contents.**

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the contents of the extracted register 50_{16} are available in Data Item 250 as described in Figure 1-2.

8.1 Roll Angle

If status bit 1 is cleared to zero (indicating that no roll angle data is available), then bits 2 through 11 must be cleared to zero. (This is covered in test 32(a) of section 8.0.) If status bit 1 is set, then the signed roll angle value in degrees is extracted from register 50_{16} as follows:

(1) Extract bit 2 as SIGN

(2) Extract bits 3 through 11 as VAL

(3) If SIGN=1, then VAL = VAL – 2^9

(4) Roll Angle (degrees) = (VAL * 90) / 2^9

Roll angle has the range of values -90,…,90 degrees measured with respect to horizontal (wings level). By convention, negative roll angles indicate counterclockwise (left wing down).

As was described in Section 3.7, the aircraft's roll angle in normal flight is a function of the true airspeed and turn rate. The relationship between roll angle 'ø' and the aircraft's true airspeed 'V' and turn rate 'w' is given by:

$$ø = \tan^{-1} \{(V * w) / g\}$$

where 'g' is the standard acceleration due to gravity (32 feet/second^2). The aircraft's turn rate 'w' is obtained from the validated track angle rate (converted to radians per second) as described in

Section 8.4. The aircraft's 'V' value is obtained from the validated true airspeed (converted to units of feet/second) as described in Section 8.5.

The extracted roll angle value is validated by comparing the computed roll angle 'ø' to the extracted roll angle. The threshold values for this comparison are defined in Section 3.7. If the airspeed value is not available (or not validated), then only a crude test can be performed using the track angle rate obtained from surveillance tracking (or the extracted value if validated). Basically, this is a right turn equals right bank sort of test. The sign of the roll angle should be the same as the sign of the track angle rate.

Test 33:	**Compare the Roll Angle value in register 50_{16} with the surveillance-derived roll angle for the aircraft (computed from turn rate and true airspeed). The test is not performed if either the turn rate (Section 8.4) or the true airspeed (Section 8.5) has not been validated from the current contents of register 50_{16}.** **If either validated turn rate or air speed is not available, then a crude roll angle test is performed using only the surveillance-derived track angle rate.**
Correct condition:	**If the aircraft's track angle rate and it's true airspeed have already been validated, then the magnitude of the difference between the Roll Angle value in register 50_{16} and the surveillance-derived roll angle for the aircraft must be less than the roll angle threshold as defined in Section 3.7.** **If either the validated turn rate or true air speed is not available from register 50_{16}, then the sign of the Roll Angle value must equal the sign of the track angle rate.**
Error condition:	**Roll Angle field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

8.2 True Track Angle

If status bit 12 is cleared to zero (indicating that no true track angle data is available), then bits 13 through 23 must be cleared to zero. (This is covered in test 32(b) of Section 8.0.) If status bit 12 is set, then the signed true track angle value in degrees is extracted from register 50_{16} as follows:

(1) Extract bit 13 as SIGN

(2) Extract bits 14 through 23 as VAL

(3) If SIGN=1, then VAL = VAL – 2^{10}

(4) True Track Angle (degrees) = (VAL * 180) / 2^{10}

Track angle has the range of values -180,…,180 degrees measured with respect to true north. By convention, negative angles indicate counterclockwise (west).

Validation of the true track angle value is performed through the comparison of the extracted true track angle value to the true track angle value computed using surveillance position reports and a tracker such as the one described in Appendix B of this report. The true track angle for a given aircraft track would be computed from the aircraft's Cartesian velocity components as:

Track Angle = ATCatan2(TRACK.XDE, TRACK.YDE)

It must be noted that the angular conventions of ATC are different from those of mathematics. ATC applications measures angles clockwise from north, while mathematics measures angles counterclockwise from the positive x-axis (east). Hence, the atan2() function of standard computing languages must be modified for this application. The function ATCatan2 (XD,YD) is defined here as:

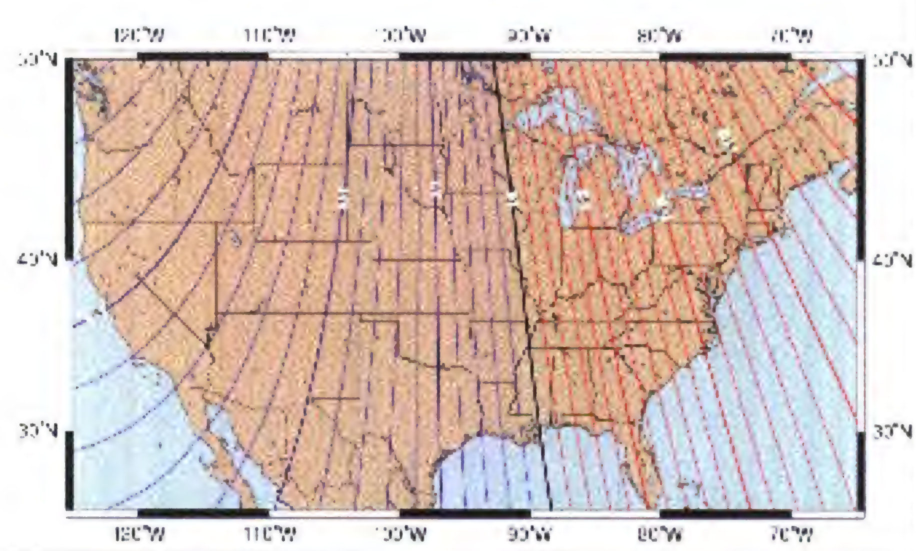
```
IF (YD = 0) THEN
  Special case for on x-axis
 IF (XD • 0) return 90
 ELSE        return -90

IF (XD = 0) THEN
  Special case for on y-axis
 IF (YD • 0) return 0
 ELSE        return 180

angle = atan( XD / YD )
angle = angle * 360 / (2 * pi) convert from radians to degrees
IF (YD • 0) THEN
 IF (XD < 0) THEN
   angle = angle + 360
ELSE
 angle = angle + 180

IF (angle > 180) THEN
 angle = angle - 360          convert to range -180..180
```

Note that the tracker described in Appendix B of this report requires three updates on a track before a valid track angle estimate can be made. No track angle validation should be performed until the fourth update of the track.

Another complication is that some Mode S surveillance sensors are calibrated with respect to magnetic north rather than geographic north. (In the U.S., terminal Mode S sensors use magnetic north as their reference.) For these sensors, the computed track angle will need to be

corrected for the magnetic deviation at the sensor (a calibration parameter). Care must be taken to use up-to-date calibration values, as the magnetic declination (difference between magnetic and true north) can vary by as much as 2 to 25 degrees per century depending on the latitude of the sensor. By convention, a positive magnetic declination indicates that magnetic north is east of true north (a clockwise rotation of the axes). Figure 8-1 (from [12]) illustrates the magnetic deviations for the continental United States. The magnetic deviation value in the continental U.S. ranges from about -20 degrees in Maine to almost +20 degrees in Washington State.

Figure 8-1: Magnetic Declination for the U.S. (2004).



Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the true track angle can be obtained from the second 16 bits of Data Item 200. The track angle is given in units of degrees (0…360) with an LSB of $360*2^{-16}$ (about 0.0055 degrees). The ASTERIX specification does not define how the sensor is to compute track angle (i.e., what sort of tracker is to be used), so care must be taken to ensure that sufficient smoothing is being performed.

The thresholds to use for comparison of the extracted true track angle and the computed true track angle are to be calculated as shown in Section 3.4. These thresholds will vary as a function of aircraft position and its direction of flight relative to the Mode S surveillance sensor.

Test 34:	**Compare the True Track Angle value in register 50_{16} with the surveillance-derived track angle for the aircraft corrected to geographic north (if required). The test is not performed if the surveillance track is not yet fully mature.**
Correct condition:	**The magnitude of the difference between the True Track Angle value in register 50_{16} and the surveillance-derived track angle for the aircraft (referenced to geographic north) must be less than the heading sigma threshold as defined in Section 3.4.**
Error condition:	**True Track Angle field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

8.3 Ground Speed

If status bit 24 is cleared to zero (indicating that no ground speed data is available), then bits 25 through 34 must be cleared to zero. (This is covered in test 32(c) of Section 8.0.) If status bit 24 is set, then the ground speed value in knots is extracted from register 50_{16} as follows:

(1) Extract 10 bits 25 through 34 as VAL

(2) Ground Speed (knots) = VAL * 2

The LSB for ground speed values is 2 knots. If the actual ground speed of the aircraft exceeds 2046 knots, then the ground speed value reported in the register will be limited to a maximum of 2046 knots.

The ground speed value is validated by comparing the extracted ground speed value to the ground speed value computed using surveillance position reports and a tracker such as the one described in Appendix B. The ground speed for a given aircraft track would be computed from its Cartesian velocity components as:

$$\text{Ground Speed} = (\text{TRACK.XDE}^2 + \text{TRACK.YDE}^2)^{0.5}$$

The tracker algorithm described in Appendix B computes the ground speed internally as TRACK.speed. This value could be used directly for validation.

Note that the tracker described in Appendix B requires three updates on a track before a valid speed estimate can be made. No ground speed validation should be performed until the fourth update of the track.

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the ground speed can be obtained from the first 16 bits of Data Item 200. The ground speed is given in units of nautical miles per second and the LSB is 2^{-14} nautical miles/second – about 0.22 knots. The ASTERIX specification does not define how the sensor is to compute ground speed (i.e., what sort of tracker is to be used), so care must be taken to ensure that sufficient smoothing is being performed.

The thresholds to use for comparison of the extracted ground speed and the computed ground speed are to be calculated as shown in Section 3.5. These thresholds will vary as a function of aircraft position and its direction of flight relative to the Mode S surveillance sensor.

Test 35:	**Compare the Ground Speed value in register 50_{16} with the surveillance-derived track speed for the aircraft. The test is not performed if the surveillance track is not yet fully mature.**
Correct condition:	**The magnitude of the difference between the Ground Speed value in register 50_{16} and the surveillance-derived speed for the aircraft must be less than the speed sigma threshold as defined in Section 3.5.**
Error condition:	**Ground Speed field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

8.4 Track Angle Rate

If status bit 35 is cleared to zero (indicating that no track angle rate data is available), then bits 36 through 45 must be cleared to zero. (This is covered in test 32(d) of Section 8.0.) If status bit 35 is set, then the signed track angle rate value in units of degrees per second is extracted from register 50_{16} as follows:

(1) Extract bit 36 as SIGN

(2) Extract bits 37 through 45 as VAL

(3) If SIGN=1, then VAL = VAL – 2^9

(4) Track Angle Rate (degrees/second) = (VAL * 16) / 2^9

Track angle rate has the range of values -16...16 degrees/second. By convention, negative values indicate counterclockwise (left). The LSB for track angle rate values is 1/32nd of a degree per second. If the magnitude of the aircraft's track angle rate exceeds 16 degrees/second, then it will be reported as 16 degrees/second with the appropriate sign. For example, a standard-rate turn in a civilian aircraft is about 3 degrees/second.

Track angle rate is validated by comparing its value to the rate of change of the surveillance track's heading as described in Section 8.2. The track angle rate at any surveillance update is given by:

$$\text{Track Angle Rate} = (\text{Track Angle}_{\text{current}} - \text{Track Angle}_{\text{previous}}) / (\text{Time}_{\text{current}} - \text{Time}_{\text{previous}})$$

The track angle rate tracker maintains a previous update's value of track angle. Hence, track angle rate validation cannot be done until one update after track angle can be obtained from the surveillance tracker. A simple smoothing algorithm might be used here to reduce fluctuations in the rate value due to measurement noise. The threshold to use for validating the track angle rate value is defined in Section 3.6.

Test 36:	**Compare the Track Rate value in register 50_{16} with the surveillance-derived heading rate for the aircraft. The test is not performed if the surveillance track is not yet fully mature.**
Correct condition:	**The magnitude of the difference between the Track Angle value in register 50_{16} and the surveillance-derived heading rate for the aircraft must be less than the heading rate sigma threshold as defined in Section 3.6.**
Error condition:	**Track Angle Rate field in EHS register 50_{16} is inconsistent with aircraft state data derived from independent ground-based surveillance.**

8.5 True Airspeed (TAS)

If status bit 46 is cleared to zero (indicating that no ground speed data is available), then bits 47 through 56 must be cleared to zero. (This is covered in test 32(e) of Section 8.0.) If status bit 46 is set, then the true airspeed value in knots is extracted from register 50_{16} as follows:

(1) Extract 10 bits 47 through 56 as VAL

(2) True Airspeed (knots) = VAL * 2

The LSB for true airspeed values is 2 knots. If the actual true airspeed of the aircraft exceeds 2046 knots, then the true airspeed value reported in the register will be limited to 2046 knots.

As is described in Appendix F of this report, the true airspeed value is a function of the local winds at the aircraft's location, the aircraft's barometric altitude, and the air temperature at the aircraft's location. The ground Mode S sensor has available the aircraft's barometric altitude data from surveillance. The air temperature can be approximated for a standard day using the equation given in Appendix F. However, there is no direct way for the ground Mode S sensor to determine the local winds. Hence, there is no way to directly validate the true airspeed value with surveillance data. However, since an aircraft whose avionics are supporting EHS also provides values of indicated airspeed (Section 9.2) and Mach (Section 9.3) in register 60_{16}, it is possible to employ the techniques from Appendix F of this report to check the three airspeed values for

consistency. Given a known altitude and any two airspeed values, it is possible to derive the air temperature. (Alternatively, just use the standard day temperature value.) With all three airspeed values, a crosscheck that each pair yields the same temperature (and that it is in reasonable agreement with the standard day value) may be used to validate the true airspeed value. The speed variation threshold value to be used is defined in Section 3.5.

A full validation of the true airspeed value is possible if the particular aircraft populates the routine meteorological register 44_{16} (see Appendix G). This register provides the values of wind speed/direction and air temperature measured on the aircraft itself. Alternatively, the true airspeed value would be validated through a coordinated test procedure where the aircraft would fly at known airspeeds.

If a large population of ELS/EHS-equipped aircraft is in the coverage of the Mode S ground sensor, it may be possible to build up a database of wind vector data by computing the offsets between ground speed/true track angle and airspeed/magnetic heading. This estimate of the current winds (a function of position and altitude) could be used to convert the surveillance-validated aircraft information (ground speed and true track angle) into measures of aircraft-derived data.

Test 37:	**Compare the True Airspeed (TAS) value in register 50_{16} with the surveillance-derived ground speed for the aircraft. The test is not performed if the surveillance track is not yet fully mature. The effect of local winds and air temperature on the aircraft's TAS must be accounted for. This may be done via extraction of the aircraft-measured wind and temperature data (see Appendix G of this report), having the aircraft fly a known TAS, or other means.** **Lacking the wind correction data, the test would involve comparing the three measures of airspeed provided by EHS (TAS in register 50_{16}, IAS and Mach in register 60_{16}) for consistency via the techniques in Appendix F.**
Correct condition:	**The magnitude of the difference between the True Airspeed (TAS) value in register 50_{16} and the surveillance-derived speed for the aircraft (corrected for the local winds and air temperature at the aircraft) must be less than the speed threshold as defined in Section 3.5. If the local wind and temperature data is not available (or correctable), then this test cannot be performed.** **Lacking the wind correction, check that TAS is consistent with the values of IAS and Mach in register 60_{16} (if available) within the speed threshold as defined in Section 3.5.**
Error condition:	**True Airspeed field in EHS register 50_{16} is inconsistent with other measures of airspeed.**

9. HEADING AND SPEED (REGISTER 60_{16}) VALIDATION

If the avionics configuration tests (see Section 2) indicate that register 60_{16} (Mode S heading and speed report) is supported by the aircraft, the contents of the register should be extracted on each scan of the surveillance sensor and the tests in this section should be performed to validate the extracted register contents. The register should not be extracted and the tests in this section should not be performed if the configuration data does not indicate support for the Mode S heading and speed transponder register (60_{16}). If the register data is already available (e.g., in a recorded data set), then the tests in this section should be performed even if the configuration data does not indicate its support.

As noted in Section 1.3, an error condition for the contents of this register may be observed occasionally due to anomalous surveillance tracking or other causes. The percentage of register 60_{16} extractions that generate error alerts should be computed for each aircraft track. While the exact threshold value for this percentage to indicate EHS non-compliance is not yet determined, it is likely to be less than 5 percent.

The Mode S heading and speed transponder register (60_{16}) contains five binary data fields. See A-9 for the complete definition of the contents of this register. Each field starts with a status bit indicating whether that data field is valid. At least one of the status bits (bit 1, 13, 24, 35, or 46) must be set to 1 for EHS support.

Test 38:	**Examine status bits 1, 13, 24, 35, and 46 in register 60_{16}. At least one of the bits must be non-zero.**
Correct condition:	**At least one of the status bits 1, 13, 24, 35, or 46 in register 60_{16} must be non-zero.**
Error condition:	**All data field status bits in EHS register 60_{16} cleared to 0. No valid data in the register.**

If the status bit for a data field is zero (indicating that there is no current data for that field), then the data bits for the field should be cleared to all zeroes.

Test 39:	**Examine status bits 1, 13, 24, 35, and 46 in register 60_{16}. If any status bit is zero, then its corresponding data bits must also be zero.**
Correct condition:	**(a) If bit 1 is zero, then bits 2...12 must be zero.**
	(b) If bit 13 is zero, then bits 14...23 must be zero.
	(c) If bit 24 is zero, then bits 25…34 must be zero.
	(d) If bit 35 is zero, then bits 36...45 must be zero.
	(e) If bit 46 is zero, then bits 47…56 must be zero.
Error condition:	**Status bit(s) cleared to 0, but corresponding data fields not cleared to 0 in EHS register 60_{16}; invalid register contents**

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [5]), then the contents of the extracted register 60_{16} are available in Data Item 250 as described in Figure 1-2.

9.1 Magnetic Heading

If status bit 1 is cleared to zero (indicating that no magnetic heading data is available), then bits 2 through 12 must be cleared to zero. (This is covered in test 39(a) of Section 9.0.) If status bit 1 is set, then the signed magnetic heading value in degrees is extracted from register 60_{16} as follows:

(1) Extract bit 2 as SIGN

(2) Extract bits 3 through 12 as VAL

(3) If SIGN=1, then VAL = VAL – 2^{10}

(4) Magnetic Heading (degrees) = (VAL * 180) / 2^{10}

Magnetic heading has the range of values -180…180 degrees measured with respect to magnetic north. By convention, negative angles indicate counterclockwise (west).

The magnetic heading of an aircraft is related (but not identical) to the aircraft's true track angle (Section 8.2). First of all, the magnetic heading is measured with respect to magnetic north at the aircraft's location while the true track angle is measured with respect to geographic north. As was described in Section 8.2, the offset between geographic and magnetic north is a parameter of the Mode S ground sensor location. For sensors not too close to the Earth's poles, using the magnetic deviation value at the sensor is precise enough (the magnetic deviation wouldn't vary

more than a degree over the coverage volume of the sensor). A more precise map of magnetic deviation versus aircraft location (determined from its surveillance track) could be used. Secondly, the aircraft's heading is impacted by the local winds at the aircraft's location – it will differ from the ground-measured true track angle just as the airspeed values (Sections 8.5, 9.2, and 9.3) will differ from the ground speed (Section 8.3).

A full validation of the magnetic heading value is possible if the particular aircraft populates the routine meteorological register 44_{16} (see Appendix G). This register provides the values of wind speed and direction measured on the aircraft itself. Alternatively, the magnetic heading value would be validated through a coordinated test procedure where the aircraft would fly at known airspeeds.

If a large population of ELS/EHS-equipped aircraft is in the coverage of the Mode S ground sensor, it may be possible to build up a database of wind vector data by computing the offsets between ground speed/true track angle and airspeed/magnetic heading. This estimate of the current winds (a function of position and altitude) could be used to convert the surveillance-validated aircraft information (ground speed and true track angle) into measures of aircraft-derived data.

Test 40:	**Compare the Magnetic Heading value in register 60_{16} with the surveillance-derived track angle for the aircraft corrected to magnetic north (if required). The test is not performed if the surveillance track is not yet fully mature. The effect of local winds on the aircraft heading must be accounted for. This may be done via extraction of the aircraft-measured wind data (see Appendix G), having the aircraft fly a known magnetic heading, or other means.**
Correct condition:	**The magnitude of the difference between the Magnetic Heading value in register 60_{16} and the surveillance-derived track angle for the aircraft (referenced to magnetic north and corrected for the local winds at the aircraft) must be less than the heading sigma threshold as defined in Section 3.4. If the local wind data is not available (or correctable), then this test cannot be performed.**
Error condition:	**Magnetic Heading field in EHS register 60_{16} is inconsistent with aircraft state data derived from surveillance and/or aircraft-specific test inputs.**

9.2 Indicated Airspeed (IAS)

If status bit 13 is cleared to zero (indicating that no indicated airspeed data is available), then bits 14 through 23 must be cleared to zero. (This is covered in test 39(b) of Section 9.0.) If status bit 13 is set, then the indicated airspeed value in knots is extracted from register 60_{16} as follows:

(1) Extract 10 bits 14 through 23 as VAL

(2) Indicated Airspeed (knots) = VAL

The LSB of the indicated airspeed value is 2 knots. If the actual indicated airspeed of the aircraft exceeds 1023 knots, then the indicated airspeed value reported in the register will be limited to 1023 knots.

As is described in Appendix F of this report, the indicated airspeed value is a function of the local winds at the aircraft's location, the aircraft's barometric altitude, and the air temperature at the aircraft's location. The ground Mode S sensor has available the aircraft's barometric altitude data from surveillance. The air temperature can be approximated for an ISA standard day using the equation given in Appendix F. However, there is no direct way for the ground Mode S sensor to determine the local winds. Hence, there is no way to directly validate the indicated airspeed value with surveillance data. However, since an aircraft whose avionics are supporting EHS also provides values of true airspeed (Section 8.5) in register 50_{16} and Mach (Section 9.3) in register 60_{16}, it is possible to employ the techniques from Appendix F of this report to check the three airspeed values for consistency. Given a known altitude and any two airspeed values, it is possible to derive the air temperature. (Alternatively, just use the ISA standard day temperature value.) With all three airspeed values, a crosscheck that each pair yields the same temperature (and that it is in reasonable agreement with the ISA standard day value) may be used to validate the indicated airspeed value. The speed variation threshold value to be used is defined in Section 3.5.

A full validation of the indicated airspeed value is possible if the particular aircraft populates the routine meteorological register 44_{16} (see Appendix G). This register provides the values of wind speed/direction and air temperature measured on the aircraft itself. Alternatively, the indicated airspeed value would be validated through a coordinated test procedure where the aircraft would fly at known airspeeds.

If a large population of ELS/EHS-equipped aircraft is in the coverage of the Mode S ground sensor, it may be possible to build up a database of wind vector data by computing the offsets between ground speed/true track angle and airspeed/magnetic heading. This estimate of the current winds (a function of position and altitude) could be used to convert the surveillance-validated aircraft information (ground speed and true track angle) into measures of aircraft-derived data.

Test 41:	**Compare the Indicated Airspeed (IAS) value in register 60_{16} with the surveillance-derived ground speed for the aircraft. The test is not performed if the surveillance track is not yet fully mature. The effect of local winds and air temperature on the aircraft's IAS must be accounted for. This may be done via extraction of the aircraft-measured wind and temperature data (see Appendix G), having the aircraft fly a known IAS, or other means.** **Lacking the wind correction data, the test would involve comparing the three measures of airspeed provided by EHS (TAS in register 50_{16}, IAS and Mach in register 60_{16}) for consistency via the techniques in Appendix F.**
Correct condition:	**The magnitude of the difference between the Indicated Airspeed (IAS) value in register 60_{16} and the surveillance-derived speed for the aircraft (corrected for the local winds and air temperature at the aircraft) must be less than the speed threshold as defined in Section 3.5. If the local wind and temperature data is not available (or correctable), then this test cannot be performed.** **Lacking the wind correction, check that IAS is consistent with the values of TAS in register 50_{16} and Mach in register 60_{16} (if available) within the speed threshold as defined in Section 3.5.**
Error condition:	**Indicated Airspeed field in EHS register 60_{16} is inconsistent with other measures of airspeed.**

9.3 Mach

If status bit 24 is cleared to zero (indicating that no Mach number data is available), then bits 25 through 34 must be cleared to zero. (This is covered in test 39(c) of Section 9.0.) If status bit 24 is set, then the Mach number value is extracted from register 60_{16} as follows:

(1) Extract 10 bits 25 through 34 as VAL

(2) Mach number = (VAL * 4) / 1000

The LSB of the extracted value is 0.004 Mach. If the actual Mach number of the aircraft exceeds 4.092, then the Mach number value reported in the register will be limited to 4.092.

As is described in Appendix F, the Mach number value is a function of the local winds at the aircraft's location, the aircraft's barometric altitude, and the air temperature at the aircraft's location. The ground Mode S sensor has available the aircraft's barometric altitude data from surveillance. The air temperature can be approximated for an ISA standard day using the equation given in Appendix F. However, there is no direct way for the ground Mode S sensor to determine the local winds. Hence, there is no way to directly validate the Mach number value with surveillance data. However, since an aircraft whose avionics are supporting EHS also provides values of true airspeed (Section 8.5) in register 50_{16} and indicated airspeed (Section 9.2) in register 60_{16}, it is possible to employ the techniques from Appendix F to check the three airspeed values for consistency. Given a known altitude and any two airspeed values, it is possible to derive the air temperature. (Alternatively, just use the ISA standard day temperature value.) With all three airspeed values, a crosscheck that each pair yields the same temperature (and that it is in reasonable agreement with the ISA standard day value) may be used to validate the Mach number value. The speed variation threshold value to be used is defined in Section 3.5.

A full validation of the Mach number value is possible if the particular aircraft populates the routine meteorological register 44_{16} (see Appendix G). This register provides the values of wind speed/direction and air temperature measured on the aircraft itself. Alternatively, the Mach number value would be validated through a coordinated test procedure where the aircraft would fly at known airspeeds.

If a large population of ELS/EHS-equipped aircraft is in the coverage of the Mode S ground sensor, it may be possible to build up a database of wind vector data by computing the offsets between ground speed/true track angle and airspeed/magnetic heading. This estimate of the current winds (a function of position and altitude) could be used to convert the surveillance-validated aircraft information (ground speed and true track angle) into measures of aircraft-derived data.

Test 42:	**Compare the Mach number value in register 60_{16} with the surveillance-derived ground speed for the aircraft. The test is not performed if the surveillance track is not yet fully mature. The effect of local winds and air temperature on the aircraft's Mach number must be accounted for. This may be done via extraction of the aircraft-measured wind and temperature data (see Appendix G), having the aircraft fly a known Mach number, or other means.** **Lacking the wind correction data, the test would involve comparing the three measures of airspeed provided by EHS (TAS in register 50_{16}, IAS and Mach in register 60_{16}) for consistency via the techniques in Appendix F.**
Correct condition:	**The magnitude of the difference between the Mach number value in register 60_{16} and the surveillance-derived speed for the aircraft (corrected for the local winds and air temperature at the aircraft) must be less than the speed threshold as defined in Section 3.5. If the local wind and temperature data is not available (or correctable), then this test cannot be performed.** **Lacking the wind correction, check that Mach number is consistent with the values of TAS in register 50_{16} and IAS in register 60_{16} (if available) within the speed threshold as defined in Section 3.5.**
Error condition:	**Mach number field in EHS register 60_{16} is inconsistent with other measures of airspeed.**

9.4 Barometric Altitude Rate

If status bit 35 is cleared to zero (indicating that no barometric altitude rate data is available), then bits 36 through 45 must be cleared to zero. (This is covered in test 39(d) of Section 9.0.) If status bit 35 is set, then the signed barometric altitude rate is extracted from register 60_{16} as follows:

(1) Extract bit 36 as SIGN

(2) Extract bits 37 through 45 as VAL

(3) If SIGN=1, then VAL = VAL – 2^9

(4) Barometric Altitude Rate (feet per minute) = VAL * 32

The LSB of the barometric rate field is 32 feet per minute. By convention, positive altitude rates indicate an aircraft climb. If the aircraft's altitude rate lies outside the range of -16,384 to +16,352 feet/minute, then the extracted value is limited to the appropriate range extreme.

The barometric altitude rate extracted from register 60^{16} is validated by comparing it to the computed altitude rate derived from an altitude tracker algorithm driven by the surveillance altitude reports. Appendix C describes an algorithm derived from the Mode S Traffic Information Service (TIS) application suitable for 100-foot flight level altitude data, while Appendix D describes an algorithm derived from the ACAS application to be used with 25-foot altitude data. It should be noted that the altitude trackers described in Appendices C and D take three surveillance updates before a stable altitude rate value is available. No altitude validation tests should be performed until the fourth surveillance update. Appendix E describes a non real-time algorithm to compute altitude rate given a recorded set of target reports. Valid altitude rates can be computed using the non real-time algorithm described in Appendix E starting with the second target report.

Note: if the input surveillance source provides ASTERIX Category 048 target reports (see [4]), then the altitude obtained from Data Item 090 can provide 25-foot resolution for those aircraft reporting 25-foot altitude data. The low-order 14 bits of data item 090 contain the altitude value in 25-foot increments. The high-order two bits of data item 090 flag conditions where the altitude data might be erroneous. If bit 16 (the validity indicator) is set, this indicates that the altitude value is too far from the aircraft track's altitude to be trustworthy. If bit 15 (the garble indicator) is set, this indicates that a bit error was detected in the Mode S response and error correction has been attempted. The altitude value might not be trustworthy.

The value of the 'D1' bit in the aircraft transponder's Gray-coded altitude bits indicates whether the aircraft is providing 25-foot altitude quantization (if set). (Only Mode S transponders can provide 25-foot quantization.) ASTERIX Category 048 target reports (see [5]) may provide the Gray-coded altitude data in Data Item 100. Bit 21 of Data Item 100 (also known as the 'Q' bit) is set to indicate 25-foot altimetry.

The test threshold for validating altitude rate is defined in Section 3.8. The threshold value is different for aircraft with 100-foot versus 25-foot altitude quantization.

Test 43:	**Compare the Barometric Altitude Rate value in register 60_{16} with the surveillance-derived altitude rate for the aircraft. The test is not performed if the surveillance track is not yet fully mature.**
Correct condition:	**The magnitude of the difference between the Barometric Altitude Rate value in register 60_{16} and the surveillance-derived altitude rate for the aircraft must be less than the altitude rate sigma threshold as defined in Section 3.8.**
Error condition:	**Barometric Altitude Rate field in EHS register 60_{16} is inconsistent with the reported rate of change in the aircraft's barometric altitude.**

9.5 Inertial Vertical Velocity

If status bit 46 is cleared to zero (indicating that no inertial vertical velocity data is available), then bits 47 through 56 must be cleared to zero. (This is covered in test 39(e) of section 9.0 above.) If status bit 46 is set, then the signed inertial vertical velocity is extracted from register 60_{16} as follows:

(1) Extract bit 47 as SIGN

(2) Extract bits 48 through 56 as VAL

(3) If SIGN=1, then VAL = VAL – 2^9

(4) Inertial Vertical Velocity (feet per minute) = VAL * 32

The LSB of the inertial vertical velocity field is 32 feet per minute. By convention, positive vertical velocities indicate climb. If the aircraft's inertial vertical velocity lies outside the range of -16,384 to +16,352 feet/minute, then the extracted inertial vertical velocity value is limited to the appropriate range extreme.

When available, the inertial vertical velocity data is derived from navigation data sources (such as the FMS) in the aircraft's avionics. These will be different from those providing barometric altitude. The inertial vertical velocity has more filtering applied and is likely to be smoother than the barometric altitude rate. However, for purposes of validation, the same procedure as that used for barometric altitude rate (see Section 9.4) is to be applied.

Test 44:	**Compare the Inertial Vertical Velocity value in register 60_{16} with the surveillance-derived altitude rate for the aircraft. The test is not performed if the surveillance track is not yet fully mature.**
Correct condition:	**The magnitude of the difference between the Inertial Vertical Velocity value in register 60_{16} and the surveillance-derived altitude rate for the aircraft must be less than the altitude rate sigma threshold as defined in Section 3.8.**
Error condition:	**Inertial Vertical Velocity field in EHS register 60_{16} is inconsistent with the rate of altitude change computed using altitude data from ground-based surveillance.**

APPENDIX A
MODE S REGISTER LAYOUTS FROM ICAO DOC 9871

This Appendix contains reproductions of the register format tables from ICAO DOC 9871 (FIRST EDITION, POST KOBE), "Technical Provisions for Mode S Services and Extended Squitter" (Reference [2]). These tables are reproduced here for ease of reference as they are discussed in this document; please see the published ICAO DOC 9871 for complete and final descriptions of the contents of the registers.

NOTE 1: the text accompanying the tables in this Appendix make references to other text and sections within DOC 9871 [2], not to text or references within this document.

NOTE 2: the ICAO standards documentation uses a different notation for hexadecimal BDS identifiers than that used in this report. ICAO uses the notation m,n where 'm' and 'n' denote 4-bit digits. Hence, GICB register 17_{16} would be denoted 1,7 in this appendix.

MB FIELD

1	MSB
2	
3	
4	BDS Code 1,0
5	
6	
7	
8	LSB
9	Continuation flag (see 9)
10	
11	
12	RESERVED
13	
14	
15	
16	Reserved for ACAS
17	MSB
18	
19	
20	Mode S subnetwork version number (see 12)
21	
22	
23	LSB
24	Transponder enhanced protocol indicator (see 4)
25	Mode S specific services capability (see 2)
26	MSB
27	Uplink ELM average throughput capability (see 13)
28	LSB
29	Downlink ELM: throughput capability of downlink ELM
30	containing the maximum number of ELM segments that the
31	transponder can deliver in response to a single requesting
32	interrogation (UF = 24). (see 14)
33	Aircraft identification capability (see 11)
34	Squitter capability subfield (SCS) (see 5)
35	Surveillance identifier code (SIC) (see 6)
36	Common usage GICB capability report (see 7)
37	
38	RESERVED FOR ACAS
39	
40	
41	MSB
42	
43	
44	
45	
46	
47	Bit array indicating the support status of DTE
48	Sub-addresses 0 to 15 (see 3 and 8)
49	
50	
51	
52	
53	
54	
55	
56	LSB

PURPOSE: To report the data link capability of the Mode S transponder/data link installation.

The coding of this register shall conform to:

1) Annex 10 Volume IV, §3.1.2.6.10.2.

2) When bit 25 is set to 1, it shall indicate that at least one Mode S specific service (other than GICB services related to registers 02_{16}, 03_{16}, 04_{16}, 10_{16}, 17_{16} to $1C_{16}$, 20_{16} and 30_{16}) is supported and the particular capability reports shall be checked.

   Note. – Registers accessed by BDS Codes 0,2; 0,3; 0,4; 1,0; 1,7 to 1,C; 2,0 and 3,0 do not affect the setting of bit 25.

3) Starting from the MSB, each subsequent bit position shall represent the DTE subaddress in the range from 0 to 15.

4) The enhanced protocol indicator shall denote a Level 5 transponder when set to 1, and a Level 2 to 4 transponder when set to 0.

5) The squitter capability subfield (SCS) shall be set to 1 if both registers 05_{16} and 06_{16} have been updated within the last ten, plus or minus one, seconds. Otherwise, it shall be set to 0.

   Note. – Registers 05_{16} and 06_{16} are used for the extended squitter Airborne and surface position reports, respectively.

6) The surveillance identifier code (SIC) bit shall be interpreted as follows:
   0 = no surveillance identifier code capability
   1 = surveillance identifier code capability

7) Bit 36 shall be toggled each time the common usage GICB capability report (register 17_{16}) changes. To avoid the generation of too many broadcast capability report changes, register 17_{16} shall be sampled at approximately one minute intervals to check for changes.

8) The current status of the on-board DTE shall be periodically reported to the GDLP by on-board sources. Since a change in this field results in a broadcast of the capability report, status inputs shall be sampled at approximately one minute intervals.

9) In order to determine the extent of any continuation of the data link capability report (into those registers reserved for this purpose: register 11_{16} to register 16_{16}), bit 9 shall be reserved as a continuation flag to indicate if the subsequent register shall be extracted. For example: upon detection of bit 9 = 1 in register 10_{16}, then register 11_{16} shall be extracted. If bit 9 = 1, in register 11_{16}, then register 12_{16} shall be extracted, and so on (up to register 16_{16}). Note that if bit 9 = 1 in register 16_{16}, then this shall be considered as an error condition.

(Requirements are continued on the next page)

Figure A-1. Data Link Capability Report (BDS Code 1,0).

10) The Mode S transponder may update bits 1-8, 16, 33, 35 and 37-40 independent of the ADLP. These bits are provided by the transponder when the data link capability report is broadcast as a result of a transponder detecte‹ change in capability reported by the ADLP (§3.1.2 of Annex 10 Volume IV).

11) Bit 33 indicates the availability of Aircraft Identification data. It shall be set l the transponder if the data comes to the transponder through a separate interface and not through the ADLP.

12) The Mode S subnetwork version number shall be coded as follows:

Version Number	Year of Annex 10 amendment	Edition of this document
0	Mode S subnetwork not available	
1	1996	---
2	1998	---
3	2002	---
4	2007	Edition 1
5 - 127	Unassigned	

Note.– RTCA/DO-181D, EUROCAE ED-73C and ED-101A are consistent with ICAO Doc 9871, Edition 1.

13) Uplink ELM average throughput capability shall be coded as follows:

0 = No UELM Capability
1 = 16 UELM segments in 1 second
2 = 16 UELM segments in 500 ms
3 = 16 UELM segments in 250 ms
4 = 16 UELM segments in 125 ms
5 = 16 UELM segments in 60 ms
6 = 16 UELM segments in 30 ms
7 = Unassigned

14) Downlink ELM throughput capability shall be coded as follows:

0 = No DELM Capability
1 = One 4 segment DELM every second
2 = One 8 segment DELM every second
3 = One 16 segment DELM every second
4 = One 16 segment DELM every 500 ms
5 = One 16 segment DELM every 250 ms
6 = One 16 segment DELM every 125 ms
7-15 = Unassigned

Figure A-1(continued). Data Link Capability Report (BDS Code 1,0).

MB FIELD

1	0,5 Extended squitter sirborne position
2	0,6 Extended squitter surface position
3	0,7 Extended squitter status
4	0,8 Extended squitter type and identification
5	0,9 Extended squitter airborne velocity information
6	0,A Extended squitter event-driven information
7	2,0 Aircraft identification
8	2,1 Aircraft registration number
9	4,0 Selected vertical intention
10	4,1 Next waypoint identifier
11	4,2 Next waypoint position
12	4,3 Next waypoint information
13	4,4 Meteorological routine report
14	4,5 Meteorological hazard report
15	4.8 VHF channel report
16	5,0 Track and turn report
17	5,1 Position coarse
18	5,2 Position fine
19	5,3 Air-referenced state vector
20	5,4 Waypoint 1
21	5,5 Waypoint 2
22	5,6 Waypoint 3
23	5,F Quasi-static parameter monitoring
24	6,0 Heading and speed report
25	Reserved for aircraft capability
26	Reserved for aircraft capability
27	E,1 Reserved for Mode S BITE (Built In Test Equipment)
28	E,2 Reserved for Mode S BITE (Built In Test Equipment)
29	F,1 Military applications
30–56	RESERVED

PURPOSE: To indicate common usage GICB services currently Supported.

1) Each bit position shall indicate that the associated register is available in the aircraft installation when set to 1.

2) All registers shall be constantly monitored at a rate consistent with their individual required update rate and the corresponding capability bit shall be set to 1 only when valid data is being input to that register at the required rate or above.

3) The capability bit shall be set to a 1 if at least one field in the register is receiving valid data at the required rate with the status bits for all fields not receiving valid data at the required rate set to ZERO (0).

4) Registers 18_{16} to $1C_{16}$ shall be independent of register 17_{16}.

Figure A-2. Common Usage GICB Capability Report (BDS Code 1,7).

MB FIELD

1	BDS 3,8
2	BDS 3,7
3	BDS 3,6
4	BDS 3,5
5	BDS 3,4
6	BDS 3,3
7	BDS 3,2
8	BDS 3,1
9	BDS 3,0
10	BDS 2,F
11	BDS 2,E
12	BDS 2,D
13	BDS 2,C
14	BDS 2,B
15	BDS 2,A
16	BDS 2,9
17	BDS 2,8
18	BDS 2,7
19	BDS 2,6
20	BDS 2,5
21	BDS 2,4
22	BDS 2,3
23	BDS 2,2
24	BDS 2,1
25	BDS 2,0
26	BDS 1,F
27	BDS 1,E
28	BDS 1,D
29	BDS 1,C
30	BDS 1,B
31	BDS 1,A
32	BDS 1,9
33	BDS 1,8
34	BDS 1,7
35	BDS 1,6
36	BDS 1,5
37	BDS 1,4
38	BDS 1,3
39	BDS 1,2
40	BDS 1,1
41	BDS 1,0
42	BDS 0,F
43	BDS 0,E
44	BDS 0,D
45	BDS 0,C
46	BDS 0,B
47	BDS 0,A
48	BDS 0,9
49	BDS 0,8
50	BDS 0,7
51	BDS 0,6
52	BDS 0,5
53	BDS 0,4
54	BDS 0,3
55	BDS 0,2
56	BDS 0,1

PURPOSE: To indicate GICB services that are installed.

Each bit position shall indicate that the GICB service that it represents has been implemented in the aircraft installation when set to 1.

Starting from the LSB, each bit position shall represent the register number, in accordance with the following table:

BDS Code	Capability installed for register
BDS 1,8	01_{16} to 38_{16}
BDS 1,9	39_{16} to 70_{16}
BDS 1,A	71_{16} to $A8_{16}$
BDS 1,B	$A9_{16}$ to $E0_{16}$
BDS 1,C	$E1_{16}$ to FF_{16}

The 25 most significant bits of register $1C_{16}$ shall not be used.

Figure A-3. Mode S Specific Services GICB Capability Report (BDS Code 1,8).

MB FIELD

1	BDS 7,0
2	BDS 6,F
3	BDS 6,E
4	BDS 6,D
5	BDS 6,C
6	BDS 6,B
7	BDS 6,A
8	BDS 6,9
9	BDS 6,8
10	BDS 6,7
11	BDS 6,6
12	BDS 6,5
13	BDS 6,4
14	BDS 6,3
15	BDS 6,2
16	BDS 6,1
17	BDS 6,0
18	BDS 5,F
19	BDS 5,E
20	BDS 5,D
21	BDS 5,C
22	BDS 5,B
23	BDS 5,A
24	BDS 5,9
25	BDS 5,8
26	BDS 5,7
27	BDS 5,6
28	BDS 5,5
29	BDS 5,4
30	BDS 5,3
31	BDS 5,2
32	BDS 5,1
33	BDS 5,0
34	BDS 4,F
35	BDS 4,E
36	BDS 4,D
37	BDS 4,C
38	BDS 4,B
39	BDS 4,A
40	BDS 4,9
41	BDS 4,8
42	BDS 4,7
43	BDS 4,6
44	BDS 4,5
45	BDS 4,4
46	BDS 4,3
47	BDS 4,2
48	BDS 4,1
49	BDS 4,0
50	BDS 3,F
51	BDS 3,E
52	BDS 3,D
53	BDS 3,C
54	BDS 3,B
55	BDS 3,A
56	BDS 3,9

PURPOSE: To indicate GICB services that are installed.

Each bit position shall indicate that the GICB service that it represents has been implemented in the aircraft installation when set to 1.

Figure A-4. Mode S Specific Services GICB Capability Report (BDS Code 1,9).

MB FIELD

1	MSB	
2		
3		
4		BDS Code 2,0
5		
6		
7		
8	LSB	
9	MSB	
10		
11		CHARACTER 1
12		
13		
14	LSB	
15	MSB	
16		
17		CHARACTER 2
18		
19		
20	LSB	
21	MSB	
22		
23		CHARACTER 3
24		
25		
26	LSB	
27	MSB	
28		
29		
30		CHARACTER 4
31		
32	LSB	
33	MSB	
34		
35		
36		CHARACTER 5
37		
38	LSB	
39	MSB	
40		
41		
42		CHARACTER 6
43		
44	LSB	
45	MSB	
46		
47		
48		CHARACTER 7
49		
50	LSB	
51	MSB	
52		
53		
54		CHARACTER 8
55		
56	LSB	

PURPOSE: To report aircraft identification to the ground.

1) Annex 10, Volume IV, §3.1.2.9.

2) The character coding to be used shall be identical to that defined in Table 3-7 of Chapter 3, Annex 10, Volume IV.

3) This data may be input to the transponder from sources other than the Mode S ADLP.

4) Characters 1 – 8 of this format shall be used by the extended squitter application.

5) Capability to support this register shall be indicated by setting bit 33 in register 10_{16} and the relevant bits in registers 17_{16} and 18_{16}.

6) The aircraft identification shall be that employed in the flight plan. When no flight plan is available, the registration marking of the aircraft shall be used.

Figure A-5. Aircraft Identification (BDS Code 2,0).

MB FIELD

1	MSB
2	
3	
4	BDS Code 3,0
5	
6	
7	
8	LSB
9	MSB
10	
11	
12	
13	
14	
15	ACTIVE RESOLUTION ADVISORIES
16	
17	
18	
19	
20	
21	
22	LSB
23	MSB
24	RACs RECORD
25	
26	LSB
27	RA TERMINATED
28	MULTIPLE THREAT ENCOUNTER
29	MSB THREAT-TYPE INDICATOR
30	LSB
31	MSB
32	
33	
34	
35	
36	
37	
38	
39	
40	
41	
42	
43	THREAT IDENTITY DATA
44	
45	
46	
47	
48	
49	
50	
51	
52	
53	
54	
55	
56	LSB

PURPOSE: To report resolution advisories (RAs) generated by ACAS equipment.

The coding of this register shall conform to:

1) Annex 10, Volume IV, §4.3.8.4.2.2.

2) Bit 27 shall mean RA terminated when set to 1.

Figure A-6. ACAS Active Resolution Advisory (BDS Code 3,0).

MB FIELD

Bit	Field	
1	STATUS	
2	MSB = 32 768 feet	
3		
4		
5	MCP/FCU SELECTED ALTITUDE	
6		
7	Range = [0, 65 520] feet	
8		
9		
10		
11		
12		
13	LSB = 16 feet	
14	STATUS	
15	MSB = 32 768 feet	
16		
17		
18	FMS SELECTED ALTITUDE	
19		
20	Range = [0, 65 520] feet	
21		
22		
23		
24		
25		
26	LSB = 16 feet	
27	STATUS	
28	MSB = 204.8 mb	
29		
30		
31		
32	BAROMETRIC PRESSURE SETTING	
33	MINUS 800 mb	
34		
35	Range = [0, 410] mb	
36		
37		
38		
39	LSB = 0.1 mb	
40		
41		
42		
43		
44	RESERVED	
45		
46		
47		
48	STATUS OF MCP/FCU MODE BITS	
49	VNAV MODE	
50	ALT HOLD MODE	MCP/FCU Mode bits
51	APPROACH MODE	
52	RESERVED	
53		
54	STATUS OF TARGET ALT SOURCE BITS	
55	MSB TARGET ALT SOURCE	
56	LSB	

PURPOSE: To provide ready access to information about the aircraft's current vertical intentions, in order to improve the effectiveness of conflict probes and to provide additional tactical information to controllers.

1) Target altitude shall be the short-term intent value, at which the aircraft will level off (or has leveled off) at the end of the current maneuver. The data source that the aircraft is currently using to determine the target altitude shall be indicated in the altitude source bits (54 to 56) as detailed below.

   Note. – This information which represents the real "aircraft intent," when available, represented by the altitude control panel selected altitude, the flight management system selected altitude, or the current aircraft altitude according to the aircraft's mode of flight (the intent may not be available at all when the pilot is flying the aircraft).

2) The data entered into bits 1 to 13 shall be derived from the mode control panel/flight control unit or equivalent equipment. Alerting devices may be used to provide data if it is not available from "control" equipment. The associated mode bits for this field (48 to 51) shall be as detailed below.

3) The data entered into bits 14 to 26 shall de derived from the flight management system or equivalent equipment managing the vertical profile of the aircraft.

4) The current barometric pressure setting shall be calculated from the value contained in the field (bits 28 to 39) plus 800 mb.

   When the barometric pressure setting is less than 800 mb or greater than 1 209.5 mb, the status bit for this field (bit 27) shall be set to indicate invalid data.

5) Bits 48 to 56 shall indicate the status (see §C.2.4.4) of the values provided in bits 1 to 26 as follows:

   Bit 48 shall indicate whether the mode bits (49, 50 and 51) are already being populated:

   0 = No mode information provided
   1 = Mode information deliberately provided

   Bits 49, 50 and 51:

   0 = Not active
   1 = Active

   Bit 54 shall indicate whether the target altitude source bits (55 and 56) are actively being populated:

   0 = No source information provided
   1 = Source information deliberately provided

   Bits 55 and 56 shall indicate target altitude source:

   00 = Unknown
   01 = Aircraft altitude
   10 = FCU/MCP selected altitude
   11 = FMS selected altitude

Figure A-7. Selected Vertical Intention (BDS Code 4,0).

MB FIELD

1	STATUS
2	SIGN 1 = Left Wing Down
3	MSB = 45 degrees
4	
5	
6	ROLL ANGLE
7	
8	Range = [-90, + 90] degrees
9	
10	
11	LSB = 45/256 degrees
12	STATUS
13	SIGN 1 = West (e.g., 315 = -45 degrees)
14	MSB = 90 degrees
15	
16	
17	TRUE TRACK ANGLE
18	
19	Range = [-180, +180] degrees
20	
21	
22	
23	LSB = 90/512 degrees
24	STATUS
25	MSB = 1 024 knots
26	
27	
28	GROUND SPEED
29	
30	Range = [0, 2 046] knots
31	
32	
33	
34	LSB = 1 024/512 knots
35	STATUS
36	SIGN 1 = Minus
37	MSB = 8 degrees/second
38	
39	
40	TRACK ANGLE RATE
41	Range = [-16, +16] degrees/second
42	
43	
44	
45	LSB = 8/256 degrees/second
46	STATUS
47	MSB = 1 024 knots
48	
49	
50	TRUE AIRSPEED
51	
52	Range = [0, 2 046] knots
53	
54	
55	
56	LSB = 2 knots

PURPOSE: To provide track and turn data to the ground systems.

1) If the value of the parameter from any source exceeds the range allowable in the register definition, the maximum allowable value in the correct positive or negative sense shall be used instead.

   Note 1. – This requires active intervention by the GFM.

2) The data entered into the register shall, whenever possible, be derived from the sources that are controlling the aircraft.

3) If any parameter is not available on the aircraft, all bits corresponding to that parameter shall be actively set to ZERO by the GFM.

4) The LSB of all fields shall be obtained by rounding.

   Note 2. – Two's complement coding is used for all signed fields as specified in §A.2.2.2.

Figure A-8. Track and Turn Report (BDS Code 5,0).

MB FIELD

Bit	Field
1	STATUS
2	SIGN 1=West (e.g., 315 = -45 degrees)
3	MSB = 90 degrees
4	
5	
6	MAGNETIC HEADING
7	
8	Range = [-180, +180] degrees
9	
10	
11	
12	LSB = 90/512 degrees
13	STATUS
14	MSB = 512 knots
15	
16	
17	INDICATED AIRSPEED
18	
19	Range = [0, 1023] knots
20	
21	
22	
23	LSB = 1 knot
24	STATUS
25	MSB = 2.048 MACH
26	
27	
28	MACH
29	
30	Range = [0, 4.092] MACH
31	
32	
33	
34	LSB = 2.048/512 MACH
35	STATUS
36	SIGN 1 = Below
37	MSB = 8 192 feet/minute
38	
39	
40	BAROMETRIC ALTITUDE RATE
41	
42	Range = [-16 384, +16 352] feet/minute
43	
44	
45	LSB = 8 192/256 = 32 feet/minute
46	STATUS
47	SIGN 1 = Below
48	MSB = 8 192 feet/minute
49	
50	
51	INERTIAL VERTICAL VELOCITY
52	
53	Range = [-16 384, +16 352] feet/minute
54	
55	
56	LSB = 8 192/256 = 32 feet/minute

PURPOSE: To provide heading and speed data to ground systems.

1) If the value of a parameter from any source exceeds the range allowable in the register definition, the maximum allowable value in the correct positive or negative sense shall be used instead.

Note 1. – This requires active intervention by the GFM.

2) The data entered into the register shall whenever possible be derived from the sources that are controlling the aircraft.

3) The LSB of all fields shall be obtained by rounding.

4) When barometric altitude rate is integrated and smoothed with inertia vertical velocity (baro-inertial information), it shall be transmitted in the Inertial Vertical Velocity field.

Note 2. – Barometric Altitude Rate contains values solely derived from barometric measurement. The Barometric Altitude Rate is usually very unsteady and may suffer from barometric instrument inertia.

Note 3. – The Inertial Vertical Velocity is also providing information on vertical movement of the aircraft but it comes from equipments (IRS, AHRS) using different sources used for navigation. The information is a more filtered and smooth parameter.

Note 4. – Two's complement coding is used for all signed fields as specified in §A.2.2.2.

Figure A-9. Heading and Speed Report (BDS Code 6,0).

APPENDIX B
EXAMPLE HORIZONTAL TRACKER ALGORITHMS

This appendix contains example horizontal tracker algorithms that may be used to derive aircraft velocity estimates from a sequence of position reports. Section B.1 describes an algorithm that may be applied real-time or to recorded data, while Section B.2 describes a non-real-time algorithm that is to be applied only to a recorded data set.

B.1 Real-Time Horizontal Tracker

The real-time horizontal tracker algorithm described in this Appendix was originally derived from [7]. The pseudo-code in this Appendix was taken from the implementation of the Traffic Information Service (TIS) deployed in all U.S. Mode S terminal sensors (Appendix XIII of [6]). The TIS horizontal tracker employs an alpha-beta algorithm augmented with a turn detection algorithm step. Tracking is performed in Cartesian x-y coordinates. Three updates are required to fully initialize a track. This tracker maintains two sets of positions and velocities – termed *internal* and *external*. The internal values are designed to provide effective turn sensing, while the external values provide a more accurate actual position for use by tracker applications. The tracker algorithm assumes that it receives an input report (coast or update) once per scan for each aircraft under surveillance. Each input REPORT structure contains at least the following fields:

REPORT.Range	Slant Range of latest update,
REPORT.Azimuth	Azimuth of latest update,
REPORT.ZR	Altitude of latest update,
REPORT.Time	Time of latest update, and
REPORT.TrackNo	Track number.

The horizontal tracker assumes the following data elements are maintained for each aircraft track in the system.

Internal x-y position	XPI,YPI
Internal x-y velocity	XDI,YDI
Vertical position	ZP
Internal firmness	FIRMI
External x-y position	XPE,YPE
External x-y velocity	XDE,YDE
External firmness	FIRME
Time of last update	last_upd_time
Horizontal State	track_state
Turn State	turn_state
Speed	speed

Each aircraft track has its horizontal state initialized to FIRST (indicating that it has seen no updates as yet) and its last update time initialized to zero. All other initialization processing will be described in Section B.1.1.

The horizontal tracker processing begins by calculating the horizontal update time. The time of the current input surveillance data for this aircraft is used as the current time value.

```
dtime_h = REPORT.Time - TRACK.last_upd_time        horizontal update
```

If dtime_h is less than or equal to zero (indicating a software timing problem), then no further horizontal tracker processing is done with this input report. If the aircraft track has seen at least two updates, the tracks horizontal positions (both internal and external) are projected to the current time as follows (using the internal velocities in order to reduce the chance of possible errors due to false turn detections).

```
dx = dtime_h * TRACK.XDI
dy = dtime_h * TRACK.YDI
TRACK.XPI = TRACK.XPE = TRACK.XPI + dx
TRACK.YPI = TRACK.YPE = TRACK.YPE + dy
```

41

If dtime_h is greater than or equal to 2 seconds, the track's last_upd_time is set to the report time.

If the current input is a coast, then the track firmnesses are updated as shown in Table B-1 and no further horizontal tracking processing is done.

Table B-1
Horizontal Tracker Firmness Update for Coasting

Current Firmness	Firmness After Coast
0	0
1	1
2	2
3	2
4	2
5	3
6	4
7	5
8	6
9	7

Otherwise, if the input message is a track update, the input handler converts the report coordinates from range-azimuth to x-y. The first step in this conversion is to calculate the report ground range using the report vertical position, ZR. (Note: the track's vertical position and velocity processing are described in Appendix C (for 100-foot flight-level altitudes), Appendix D (for 25-foot altitudes), and Appendix E (for non real-time processing)). Two altitude consistency checks are performed as follows:

1) If the absolute value of the difference between the report altitude ZR and the track altitude TRACK.ZP is greater than 9000 feet, then TRACK.ZP is used instead of ZR in computing ground range.

2) If the altitude rate (absolute altitudereg difference divided by the altitude update period dtime_z) is greater than or equal to 85 feet/second, then TRACK.ZP is used instead of ZR in computing ground range.

These checks prevent altitude errors from causing overflow problems later in the tracker. Ground range and the input report azimuth are used to compute the report x-y coordinates (denoted REPORT.XR, REPORT.YR here). Next, the tracker is called to update the horizontal components of the track.

B.1.1 Initialization State

The horizontal track update to a track whose horizontal track state is FIRST is done as follows:

1) Set the internal x-y track positions to report x-y position,
2) Set the external x-y track positions to report x-y position,
3) Set the track vertical position to report vertical position, and
4) Update the horizontal track state to SECOND

B.1.2 Second Report State

The horizontal track update to a track whose horizontal track state is SECOND repeats steps (1) through (3) of the FIRST state above. Next, the horizontal track state is updated to THIRD. The track turn_state is initialized to NOTURN and the horizontal tracker computes the x-y velocity components:

```
xvel = (REPORT.XR - TRACK.XPE) / dtime_h
yvel = (REPORT.YR - TRACK.YPE) / dtime_h
```

A check is made that these velocities are reasonable. If either velocity is greater than or equal to 2000 knots (indicating a software problem, probably in the computed value of dtime_h), the track state is reset to FIRST. Otherwise, the track horizontal velocity values are initialized as follows:

```
XDI = XDE = xvel
YDI = YDE = yvel
```
$$TRACK.speed = (xvel^2 + yvel^2)^{0.5}$$

B.1.3 Mature Track State

Tracks whose track state is neither FIRST nor SECOND perform their horizontal track update as described here. The track state is set to MATURE. The horizontal tracker uses an alpha-beta smoothing algorithm to update the track horizontal positions. A turn detection algorithm is used to further update the track velocities if a turn is detected. Both the internal and external track position estimates are propagated into the future. The reason for these two types of estimates is that the internal positions are designed to provide effective turn sensing, while the external estimates provide more accurate actual positions for the alert generation process. The track's ground speed is also calculated here.

B.1.3.1 Smoothing/Prediction

The smoothing and prediction processing of the tracker uses a standard alpha-beta algorithm as described below. The alpha and beta values used are a function of the track firmness values as defined in the Table B-2. (These values were derived empirically.) The table also includes the new firmness to use as a result of the update process.

Table B-2
Alpha, Beta, and Firmness Updates

Firmness	Alpha	Beta	New Firmness
0	1.000	0.000	2
1	1.000	1.000	3
2	1.000	1.000	3
3	0.833	0.700	4
4	0.700	0.409	5
5	0.600	0.270	6
6	0.524	0.192	7
7	0.464	0.144	8
8	0.417	0.122	9
9	0.400	0.100	9

A reasonability test is applied to the track horizontal speeds. If the track has appeared to move at an unreasonable speed (i.e., more than 2000 knots), no further smoothing or turn detection will be performed. (Note: in general, such excessive apparent speeds are the result of timing or correlation errors in the sensor's input data. This test protects against overflows, etc. in the horizontal tracking procedures.)

```
test = 2000 knots * dtime_h      maximum legal distance allowed
DIX = REPORT.XR - TRACK.XPI
DIY = REPORT.YR - TRACK.YPI
IF (|DIX| < test) AND (|DIY| < test) THEN
  Track speeds will be reasonable, do smoothing and turn detection
  alpha = alphaTable[TRACK.FIRMI]    From Table B-2
  beta = betaTable[TRACK.FIRMI]
  XA = TRACK.XPI + alpha * DIX
  YA = TRACK.YPI + alpha * DIY
  XDA = TRACK.XDI + (beta * DIX / dtime_h)
  YDA = TRACK.YDI + (beta * DIY / dtime_h)
  Perform turn detection algorithm (see section B.1.3.2 below)
  TRACK.XPI = XA
  TRACK.YPI = YA
  DEX = REPORT.XR - TRACK.XPE
  DEY = REPORT.YR - TRACK.YPE
  alpha = alphaTable[TRACK.FIRME]       From Table B-2
  TRACK.XPE = TRACK.XPE + (alpha * DEX)
```

```
TRACK.YPE = TRACK.YPE + (alpha * DEY)
update TRACK.FIRMI and TRACK.FIRME   From Table B-2
```

B.1.3.2 Turn Sensing

After the alpha-beta smoothing is completed, the horizontal tracker performs the turn detection algorithm to update the horizontal velocities. Note that tracks that have extremely small speeds (indicating an aircraft stopped or taxiing on the ground) do not go through horizontal velocity update. This is done because the velocity would be largely composed of positional measurement noise and would not be reliable. An empirically derived threshold of 5 knots is used to determine whether the horizontal velocity update processing is to be performed.

```
A = (DIX * TRACK.YDI) - (DIY * TRACK.XDI)
S = sign(A)   +1, 0, or -1
B = TRACK.XDI^2 + TRACK.YDI^2
IF (B = 0) THEN D2 = infinity  D2=square of cross-track distance
ELSE    D2 = A^2 / B
R2A = XA^2 + YA^2
V2A = XDA^2 + YDA^2
TRACK.speed = (V2A)^0.5
IF (TRACK.speed > 5 knots) THEN
  Compute turn threshold for D2 as a function of track range, speed,
     and orientation
  STDA = 150 feet           radial error expressed in feet
  STDB = 0.002 * (R2A)^0.5   tangential error expressed in feet
  vak = (V2A)^0.5            expressed in knots
  DTHA = (3.1 * STDA + 1.35 * vak)^2
  DTHB = (3.1 * STDB + 1.35 * vak)^2 - DTHA
  D2TH = DTHA + DTHB * (XA * XDA + YA * YDA)^2 / (V2A * R2A)
```

The turn threshold D2TH is multiplied by an empirically derived constant thk that is a chosen from Table B-3 based on the track's firmness. The value of thk is effectively infinite (10^{10}) for track firmness values less than 3.

Table B-3
THK Value as a Function of Track Firmness

Firmness	THK
0	10^{10}
1	10^{10}
2	10^{10}
3	3.60
4	2.00
5	1.50
6	1.26
7	1.12
8	1.03
9	1.00

```
thk = THK[TRACK.FIRMI] From Table B-3
D2TH = D2TH * thk
IF (D2 • D2TH) THEN
  No turn detected, update velocities
  TRACK.turn_state = NOTURN
  TRACK.XDI = TRACK.XDE = XDA
  TRACK.YDI = TRACK.YDE = YDA
ELSE
  Turn detected, compute velocity corrections
  DRX = DIX + dx          dx,dy calculated at start of Appendix B
  DRY = DIY + dy
  C = DRX * XDA + DRY * YDA
  P = sign(C)
  CP2 = C^2 / [ (DRX^2 + DRY^2) * V2A]
  CT2 = [cos(20 degree turn)]^2     constant value
  IF (P * CP2 • CT2) THEN
     Default turn correction
     SDT = sin(10 degrees of turn) constant values
     CDT = cos(10 degrees of turn)
  ELSE
     Compute turn correction
     CP = (CP2)^0.5
     SDT = [0.5 * (1 - CP)]^0.5
     CDT = [0.5 * (1 + CP)]^0.5
     TRACK.XDI = XDA * CDT + (S * SDT * YDA)
     TRACK.YDI = YDA * CDT - (S * SDT * XDA)
     IF (S = TRACK.turn_state) THEN
      Same direction as last update, extra external turn correction
      SDEL = sin(15 degrees of turn)  constant values
      CDEL = cos(15 degrees of turn)
```

```
 TRACK.XDE = TRACK.XDI * CDEL + (S * SDEL * TRACK.YDI)
 TRACK.YDE = TRACK.YDI * CDEL - (S * SDEL * TRACK.XDI)
ELSE
 Not same direction as last update
 TRACK.XDE = TRACK.XDI
 TRACK.YDE = TRACK.YDI
 TRACK.turn_state = S
```

B.2 Non-Real-Time Horizontal Path Smoother

The horizontal tracker algorithm described in Appendix B.1 above was designed to operate in real-time. However, if all the target reports for the aircraft's trajectory are simultaneously available (as from a previously recorded dataset), then a non-real-time off-line algorithm can be applied to gain a more-accurate determination of truth via the ability to look both ahead and back through the data in the processing of each aircraft track. For the purposes of the discussion in this appendix, it is assumed that the target report positions for a given aircraft's flight are accessible as an array of structures denoted here as TRACK[1...N]. Each target report structure in the TRACK array is assumed to have the following elements:

(a) Cartesian X-coordinate,

(b) Cartesian Y-coordinate, and

(c) Time of measurement.

The conversion of the sensor's range-azimuth coordinates to Cartesian coordinates (the origin is assumed to be at the sensor) is done using the aircraft's reported altitude in the calculation of ground range (see Section 3.3). If the target report lacks altitude data, then the lesser of 0.5 nautical miles or one-half of the target range is assumed for the altitude. The use of Cartesian coordinates make it easier to compute the track's velocity components and remove the need to be concerned with the inter-dependence of the sensor's range and azimuth measurements when the aircraft is close to the sensor.

The non-real-time horizontal tracker algorithm makes two passes through the aircraft track. The first pass is intended to remove any outlier points that might have resulted from faulty correlation processing or other types of data error. Once the outlier points have been flagged, a second pass through the track data is used to compute a smoothed truth position and track velocity vector for each valid target report.

B.2.1 Outlier Removal Pass

The outlier removal pass of the algorithm treats each data entry i from TRACK[4] through TRACK[N-3]. A 7-point quadratic curve-fit algorithm (described in B.2.3) is performed for each set of points (i-3) through (i+3) in both Cartesian coordinates versus time. A quadratic fit is able to smoothly follow an aircraft's turn without being susceptible to data noise. The use of a 7-point fit has proven to be a good compromise between adequate smoothing and responsiveness to real aircraft maneuvers.

The smoothed Cartesian position of the aircraft at the time of target report i is computed (using the curve-fit coefficients computed for report i) and its separation distance from the actual target report position is calculated. Assuming that the quadratic curve-fit algorithm described in B.2.3 has been performed for both the X[] and Y[] coordinates of this point, the separation distance for report i is computed as follows:

$$\mathrm{Distance}(i) = [(\mathrm{XFIT}[i] - X[i])^2 + (\mathrm{YFIT}[i] - Y[i])^2]^{0.5}$$

If this separation distance exceeds a reasonability threshold, then TRACK[i] is declared to be an outlier. Target reports declared to be outliers are not used in further processing. (Note: a particularly noisy track might have too many outlier points to be fit successfully using this algorithm. Some sort of check for multiple outliers in a sequence of seven reports might be required. Only the track entry having the largest separation distance (in the sequence of seven reports) would be declared an outlier.

The outlier separation reasonability threshold is calculated as a function of the aircraft's position with respect to the sensor and the sensor's measurement accuracy. Section 3.3 describes how to compute the measurement error sigma values for a surveillance position report in Cartesian coordinates. A system parameter "n" (nominally three) is multiplied by the sensor measurement error sigmas to derive the outlier separation threshold in Cartesian coordinates. The separation distance reasonability threshold is given simply as:

$$\mathrm{Distance\ Threshold} = [\ (n * \mathrm{SigmaX})^2 + (n * \mathrm{SigmaY})^2\ ]^{0.5}$$

B.2.2 Smoothing Pass

Once the outliers have been removed from the track data, a second pass is performed to smooth the aircraft's track and derive the velocity components. As was the case for the outlier removal pass, each valid data entry "i" from TRACK[4] through TRACK[N-3] is fit with a 7-point quadratic polynomial – from (i-3) through (i+3) – as described in B.2.3. The smoothed position of the aircraft at the time of target report i is computed – this is considered the true position of the aircraft for this time.

The aircraft's track velocity components for the time of target report i are computed from the smoothed positions of the track at time of target reports (i-1) and (i+1) – using the quadratic polynomial curve-fit for time of target report i. The Cartesian velocity components are given by:

```
DeltaT = TRACK[i+1].time - TRACK[i-1].time
Xdot[i] = (TRACK[i+1].smooth_X - TRACK[i-1].smooth_X) / DeltaT
Ydot[i] = (TRACK[i+1].smooth_Y - TRACK[i-1].smooth_Y) / DeltaT
```

There needs to be a protection test that the computed value of DeltaT is non-zero. If DeltaT is zero (indicating a likely timing problem in the data), then set both Cartesian velocity components to zero.

B.2.3 Quadratic Curve-Fit Algorithm

The following pseudo-code describes how to perform a quadratic (second-order) curve-fit for a set of seven data points, denoted here as the arrays P[7] (denoting a position in a Cartesian coordinate – either X[] or Y[]) and Time[7] (time for the particular position coordinate value). The pseudo-code in this section is a specific case of a generalized Gauss-Jordan algorithm that is found in many computer mathematics packages. The pseudo-code in this section uses the convention that array indices start with 0. The curve-fit algorithm returns the following data:

PFIT[7]:	The value fit to each data point (for the input Cartesian coordinate)
COEFF[3]:	The calculated coefficients of the quadratic equation fit to the data

Quadratic equations all have 3 coefficients – constant, linear, and second-order.

The first step of the curve fitting process is to initialize all the entries of the coefficient array COEFF[3] to zero. A copy of the input data point values is made – denoted here as PC[7]. The copy of the position values is made so that the subsequent process of curve fitting does not impact the original data values from the calling program.

The second step of the curve fitting process is to compute the maximum and minimum values in the input data array P[7]. The sum of all the P[] entries (denoted Psum) is also computed here. This processing looks for the special case (fairly common) of a straight line where the full curve-fit process is not necessary.

```
Pmax = P[0]
Pmin = P[0]
Psum = P[0]
FOR i=1 THROUGH 6
    IF P[i] > Pmax THEN Pmax = P[i]
    IF P[i] < Pmin THEN Pmin = P[i]
    Psum = Psum + P[i]
```

If the maximum and minimum values in the input data are nearly equal (the threshold for straightness of 0.01 nautical miles was chosen empirically), then the data is a special case – a nearly straight line. This special case is handled as follows:

```
IF (Pmax - Pmin) < 0.01 THEN   special case for a line
    Paverage = Psum / 7.0      average of the coordinate values
    COEFF[0] = Paverage        only constant term is nonzero
    FOR i=0 THROUGH 6
           PFIT[i] = Paverage
```

If the data points cannot be fit with a straight line, the midpoint P[] value (Pmax – Pmin) / 2) is subtracted from each of the PC[] values in order to normalize them and the curve-fit processing continues as described below.

The third step of the curve fitting process is to calculate the normal equations. Three local doubly-dimensioned arrays are used in this computation: G[3][4], Q[7][4], and PP[3][7]. The first dimension of the G array is degree of the fit (quadratic in this case) plus 1, while the second dimension is one larger. All the elements of the G[][] array are initialized to zero. The first dimension of the Q array is the number of input data points used in the curve-fit (seven in this case), while the second dimension is the degree of the curve-fit plus two (the extra storage holds the Time values). The Q[][] array is initialized as follows:

```
FOR i=0 THROUGH 6
   Q[i][0] = 1.0
   Q[i][3] = Time[i]

FOR j=0 THROUGH 1
   FOR i=0 THROUGH 6
         Q[i][j+1] = Q[i][j] * PC[i]
```

The PP[][] array is then computed as the transpose of the Q[][] array as follows:

```
FOR j=0 THROUGH 2
   FOR i=0 THROUGH 6
         PP[j][i] = Q[i][j]
```

The G[][] array is then computed from the PP[][] and Q[][] arrays as follows:

```
FOR i=0 THROUGH 2
   FOR j=0 THROUGH 3
         FOR k=0 THROUGH 6
               G[i][j] = G[i][j] + (PP[i][k] * Q[k][j])
```

Solving the normal equations is done with the Gauss-Jordan reduction algorithm as follows:

```
FOR k=0 THROUGH 2
   FOR j = (k+1) THROUGH 3
         G[k][j] = G[k][j] / G[k][k]

   FOR i=0 THROUGH 2
         IF (i-k) • 0 THEN
               FOR j=(k+1) THROUGH 3
                     G[i][j] = G[i][j] - (G[i][k] * G[k][j])
```

The calculated normal equation coefficients are then copied from the G[][] array to the COEFF[] array as follows (this is not required if only the curve-fit coordinate values denoted PFIT[] described below are used in further processing):

```
FOR k=0 THROUGH 2
    COEFF[k] = G[k][3]
```

The fourth and final step of the curve fitting process is to compute the seven curve-fitted point values for each of the seven data points for the input coordinate -- denoted as the array PFIT[7]. This process uses a local array denoted ALPHA[7] that is initialized to zero. The curve fitting procedure is done as follows for each Cartesian coordinate (this process uses the equation coefficients to solve for each point):

```
FOR k=0 THROUGH 6
    FOR i=0 THROUGH 2
           ALPHA[2-i] = G[i][3]

    FOR j=0 THROUGH 1
           ALPHA[j+1] = ALPHA[j+1] + (ALPHA[j] * PC[k])

    PFIT[k] = ALPHA[2]
```

APPENDIX C
100 FOOT FLIGHT LEVEL VERTICAL TRACKER ALGORITHM

The vertical tracker algorithm used in the Traffic Information Service (TIS) is a variation on the algorithm originally developed for ACAS applications (see [8]). It is a multi-state algorithm that measures the time spent by a track at each altitude level and estimates the time between altitude level transitions. Such a multi-state procedure is better able to generate accurate vertical velocity estimates than a simpler alpha-beta algorithm (such as that used for the horizontal TIS tracker), since the altitude data is coarsely quantized (to 100-foot flight levels) and aircraft may spend large amounts of time between level transitions – leading to erratic estimates of the aircraft's altitude rate. The expression of the vertical tracker algorithm in pseudo-code given this Appendix is derived from Appendix XIII of [6]. The TIS tracker assumes that it receives an input surveillance target report (coast or update) once per scan for each aircraft under surveillance.

The vertical tracker assumes the following data elements are maintained for each aircraft track in the system:

Vertical position	ZP,
Vertical velocity	ZD,
Time of last altitude update	alt_upd_time,
Altitude State	alt_state,
Vertical position used in last rate update	ZPR,
Smoothed altitude residual	resid,
Extent of altitude trend	alt_trend_time,
Time of last altitude transition	alt_trans_time,
Time since altitude rate was estimated	alt_rate_time,
Uncertainty in altitude transition time	alt_guess_time,
Altitude transition since transition time	alt_trans_diff, and
Sign of last altitude transition	alt_direction.

The tracker states are denoted:

INIT	initial state, first time for track or after re-initialization,
GUESS	single un-reinforced altitude transition, rate uncertain,
TREND	an altitude trend has been declared,
LEVEL	level flight,
RESET	need to reset the rate, residual got too large, and
TOZERO	reducing rate towards zero.

The altitude fields for each aircraft are initialized as follows, where scantime is the update period of the Mode S sensor providing the input surveillance reports. The parameter scantime denotes the sensor's scan period in appropriate time units.

```
TRACK.alt_state = INIT
```

```
TRACK.alt_upd_time = REPORT.time - scantime       1 scan ago
TRACK.alt_trend_time = scantime
TRACK.alt_trans_time = -scantime
TRACK.alt_rate_time = 0
TRACK.resid = 0
TRACK.alt_trans_diff = 0
TRACK.ZP = REPORT.ZR
TRACK.ZPR = REPORT.ZR
TRACK.ZD = 0
```

C.1 Vertical Tracker Driver/Handler

The first step of the vertical tracker algorithm is to compute the update and transition times as follows:

```
dtime_z = REPORT.time - TRACK.alt_upd_time         vertical update
dtime_trans = REPORT.time - TRACK.alt_trans_time  transition
```

If dtime_z is less than or equal to zero, or dtime_trans is equal to zero (indicating a software timing problem), no further track update processing is done. If both time computed time periods are positive, the input handler can proceed to compute a vertical position ZR from the message altitude if the input is a track update and the altitude type is available. If the message is a coast or drop, or the altitude not available, ZR is set to the track's vertical position TRACK.ZP (if the track is not in its initial state), or to the lesser of 0.5 nautical miles and one-half of the track's range (if the track is in its initial state). (The sensor uses an equivalent altitude assumption in computing ground range for aircraft tracks that have never had a reported clear altitude.)

The overall driver for the altitude tracker first computes the altitude that the track would have if projected to the current time.

```
coast_alt = TRACK.ZPR + (dtime_z * TRACK.ZD)
```

If the report for this update does not have an altitude, or if this update is a coast, then the track's vertical position is set to coast_alt and the following check for excessive altitude coasting performed:

```
IF (dtime_z > 4 scans) THEN
  This track coasted too long, reset its altitude fields
  TRACK.alt_state = INIT
  TRACK.alt_trend_time = scantime
  TRACK.alt_trans_time = -scantime
  TRACK.alt_rate_time = 0
  TRACK.resid = 0
  TRACK.alt_trans_diff = 0
  TRACK.ZD = 0
```

If the check passes and the track's altitude fields are reset, no further altitude processing is performed.

Next, the altitude tracker driver sets the values of local variables to be used by the processing for the various altitude tracker states (see sections C.2 through C.5).

```
trans_diff = REPORT.ZR - TRACK.ZPR
TRACK.alt_trans_diff = trans_diff
trans_sign = sign(trans_diff)
climbing (+), descending (-), or level (0)
atrans_diff = |trans_diff|
trans_rate = trans_diff / dtime_trans
IF (atrans_diff • 1 flight level) THEN trans_flag = TRUE
ELSE                                   trans_flag = FALSE
```

If the track's altitude state is INITIALIZE, then the processing for the initialization state is performed (Section C.2). Otherwise, the altitude tracker checks that the apparent altitude acceleration is reasonable. (This checking keeps erroneous altitude jumps due to Mode C bit errors from upsetting the tracked altitude and altitude rate.) One flight level error tolerance is allowed.

```
alt_diff = |coast_alt - REPORT.ZR|
IF (alt_diff > 6000 feet) THEN
  Altitude jump too large, treat as coast, no further processing
   TRACK.ZP = REPORT.ZR
   Return

accel = 2 * (alt_diff - 1 flight level) / dtime_z^2
IF (accel > 64 feet/sec^2) THEN
  Acceleration too large (> 2g), treat as coast, no further
     processing
   TRACK.ZP = REPORT.ZR
   Return
```

If the value of trans_flag is TRUE, then the Transition State update procedure is performed (Section C.4) -- otherwise, the No Transition State update procedure is performed (Section C.3). If the track's altitude state after these procedures is TREND and the absolute value of the track's altitude residual is greater than 1.05 flight levels (i.e., 105 feet), then the RESET Smoothing procedure is performed (Section C.5).

For both the INITIALIZATION and other altitude track states (unless the track has been coasted in altitude), the following steps are performed to complete the altitude tracking function.

```
IF (trans_flag = TRUE) THEN
  Start of an altitude transition
  TRACK.alt_trans_time = REPORT.time
```

```
  TRACK.alt_direction = trans_sign

TRACK.alt_rate_time = REPORT.time - TRACK.alt_upd_time
TRACK.alt_upd_time = REPORT.time
TRACK.ZP = TRACK.ZPR = REPORT.ZR
IF (TRACK.alt_trend_time > 16 seconds) THEN
  TRACK.alt_trend_time = 16 seconds   limit trend duration

dt = REPORT.time - TRACK.alt_trend_time
IF (TRACK.alt_trans_time < dt) THEN TRACK.alt_trans_time = dt

TRACK.ZP = REPORT.ZR
TRACK.ZPR = REPORT.ZR
```

C.2 Initialization State

The processing for a track whose altitude state is being initialized is performed as follows. The initialization of the track altitude fields and local variables was described in Section C.1.

```
IF (atrans_diff > 1 flight level) THEN
  Have had a significant altitude change
  TRACK.alt_state = GUESS unsure about altitude rate
  TRACK.alt_trend_time = 0.2 * scantime     assume a time
  TRACK.ZD = ((atrans_diff - 0.75 flight levels) * trans_sign) /
     dtime_trans
  TRACK.residual = 0.85 * TRACK.residual + TRACK.alt_trans_diff -
     (TRACK.ZD * dtime_z)
ELSE
  Basically level, no significant altitude change
  TRACK.alt_trend_time = TRACK.alt_trend_time - TRACK.alt_rate_time
  IF (REPORT.alt_type = CLEAR_LEVEL) THEN
     IF (dtime_trans > 6 seconds) THEN TRACK.alt_state = LEVEL
```

C.3 No Transition State

The processing for a track update during which there has not been an altitude transition is performed as follows. The basic operation is to update the track's altitude state variable, vertical velocity, and altitude residual. The setting of the local variables was described in Section C.1.

```
No division by 0
dtime = dtime_trans - [1 flight level / ( |TRACK.ZD| + 1.e-10)]
IF (dtime > 2.5 * scantime) THEN TRACK.alt_state = TOZERO
IF (dtime_trans > 15 seconds) THEN TRACK.alt_state = LEVEL
IF (TRACK.alt_state = RESET) THEN TRACK.alt_state = TREND
IF (TRACK.alt_state != TREND) THEN
```

```
  TRACK.ZD = 0.7 * TRACK.ZD      reduce the vertical velocity

TRACK.alt_trend_time = TRACK.alt_trend_time + dtime_z
TRACK.residual = 0.85 * TRACK.residual + TRACK.alt_trans_diff -
    (TRACK.ZD * dtime_z)        Smooth the altitude residual
```

C.4 Transition State

The altitude tracker processing described below is performed for a track whose updating report indicates an altitude level transition has occurred since the last update. Different processing is done depending on the track's altitude state. Setting of the local variables was described in Section C.1.

```
CASE RESET:
  TRACK.alt_state = TREND    become a trend

CASE TREND:
  Adjust trend time at start of acceleration
  IF (trans_sign = TRACK.alt_direction) THEN
    IF (TRACK.alt_trend_time > 10 seconds) THEN
    Check for early altitude transition
    azd = 1.0 / (|TRACK.ZD| + 1.e-10) no divide by zero
    dt = (1 flight level * dtime_trans / atrans_diff) - (1 flight
        level * azd)
    IF (dt < (-1.42 * scantime + TRACK.alt_guess_time)) THEN
     Reset needed due to early altitude transition
     TRACK.alt_state = RESET
     TRACK.residual = 0
     TRACK.alt_trend_time = dtime_trans + (0.2 * scantime)
     Smooth the altitude residual
     TRACK.ZD = (0.15 * TRACK.ZD) + (0.85 * trans_rate)

  Smooth the vertical velocity
  beta = 1.0 / (1.0 + 0.75 * TRACK.alt_trend_time / dtime_trans)
  IF (beta < 0.1) THEN beta = 0.1
  TRACK.ZD = (TRACK.ZD * (1.0 - beta)) + (beta * trans_rate)
  Smooth the altitude residual
  TRACK.residual = 0.85 * TRACK.residual + TRACK.alt_trans_diff -
     (TRACK.ZD * dtime_z)
  TRACK.alt_trend_time = TRACK.alt_trend_time + dtime_z

CASE LEVEL:
  TRACK.residual = 0
  TRACK.alt_trend_time = dtime_z
  IF (atrans_diff > 1 flight level) THEN
    Beginning of an altitude trend
```

```
    TRACK.alt_state = TREND
    time = dtime_z + TRACK.alt_guess_time
    TRACK.ZD = TRACK.alt_trans_diff / time
  ELSE
    Have to guess at the altitude rate
    TRACK.alt_state = GUESS
    TRACK.ZD = (0.25 flight levels) * trans_sign / dtime_trans

CASE GUESS:  same processing for both GUESS and TOZERO states
CASE TOZERO:
  IF (trans_sign = TRACK.alt_direction) THEN
    Current trend is continuing
    TRACK.alt_state = RESET
    time = (0.2 * scantime) + (0.5 * TRACK.alt_guess_time)
    IF (atrans_diff > 1 flight level) THEN
     time = time + dtime_z
     TRACK.alt_trend_time = dtime_z
    ELSE
     time = time + dtime_trans
     TRACK.alt_trend_time = dtime_trans

    TRACK.ZD = TRACK.alt_trans_diff / time
  ELSE
    Trend is changing, reset its velocity
    TRACK.ZD = 0
    TRACK.alt_trend_time = 0.2 * scantime
    TRACK.alt_state = GUESS

  TRACK.residual = 0
  TRACK.alt_guess_time = (dtime_z - scantime) * atrans_diff /
     (1 flight level)
```

No processing is done here for the INITIALIZE altitude state (it should never be encountered at this point in the altitude tracker processing).

C.5 Reset Smoothing State

The altitude tracker processing is performed as described below for a track whose altitude residual has grown too large (indicating a missed transition). The vertical velocity and residual are modified, depending on whether the current altitude direction (up, down, or level) is consistent with the previous altitude update for this track. Setting of the local variables was described in Section C.1.

```
IF (trans_sign != TRACK.alt_direction) THEN
  Altitude change is zero or other direction, reset rate towards
     zero
```

```
  TRACK.alt_state = TOZERO
  TRACK.residual = 0
  TRACK.alt_trend_time = dtime_trans
  test_rate = 1 flight level / dtime_trans
  IF (atrans_diff > 1 flight level) THEN
    TRACK.ZD = 0.1 * test_rate * trans_sign reset the vertical rate
  ELSE
    Small change in altitude (less than 1 flight level)
    IF (|TRACK.ZD| • test_rate) THEN
      trate = 0.6 * test_rate * sign(TRACK.ZD)
      TRACK.ZD = TRACK.ZD - trate
    ELSE
      TRACK.ZD = 0.4 * TRACK.ZD
ELSE
  Altitude change consistent with last update, reset rate
  TRACK.alt_state = RESET
  TRACK.residual = 0.15 * TRACK.residual
  TRACK.alt_trend_time = dtime_trans - (0.2 * scantime)
  test_rate = trans_rate - TRACK.ZD
  IF (|test_rate| > 1.3 flight levels / scantime) THEN
    Alpha-Beta smooth the vertical velocity
    temp = (1 flight level * sign(test_rate))
    TRACK.ZD = 0.85 * (TRACK.alt_trans_diff - temp) / dtime_z
  ELSE
    TRACK.ZD = (0.15 * TRACK.ZD) + (0.85 * trans_rate)
```

APPENDIX D
25 FOOT ALTITUDE TRACKER ALGORITHM

The algorithm described here to track aircraft altitudes quantized in 25-foot increments was derived from the "air data" function of ACAS (see [9]). It is a straightforward alpha-beta technique with an added credibility check function. This algorithm is much simpler than the 100-foot altitude tracker algorithm described in Appendix C, since the finer altitude quantization does not have large data hops over short measurement intervals (typically one Mode S radar sensor scan – approximately 5 to 12 seconds). The parameters incorporated into the following pseudo-code were determined empirically.

The following altitude tracker data fields are assumed for each aircraft track:

Z	tracked altitude,
ZD	tracked altitude rate,
TDAT	time of most-recent smoothing,
TUPD	time of most-recent altitude data input,
CREDIBLE	flag for reasonable altitude data, and
SOFT	track's altitude rigidity value (2..10).

At each surveillance input, the tracker is called with ZIN (25-foot quantized altitude) and TIN (time of ZIN measurement). For the first update on a given track, the following initializations are performed.

```
TRACK.Z = ZIN
TRACK.ZD = 0
TRACK.TDAT = TIN
TRACK.TUPD = TIN
TRACK.SOFT = 10      maximum value allowed
TRACK.CREDIBLE = TRUE
```

For each subsequent surveillance input, the following algorithm is performed. The altitude predicted for the current time, ZPRED, is checked against the input altitude ZIN for credibility. If it is a credible update to the aircraft track, then an alpha-beta smoothing function is applied to the track's Z and ZD values. (Alpha is given the empirically determined value of 0.58 and beta is given the value of 0.25 in this example.) The track's softness value is decreased by one (limited to a minimum value of 2). If the ZIN value for this altitude update is not considered credible, then the track's altitude is reset to the predicted value and the track's softness increased by one (limited to a maximum value of 10).

```
ZDIFF = ZIN - ZPRED
ZPRED = TRACK.Z + TRACK,ZD * (TIN - TRACK.TUPD)
IF ABS( ZDIFF ) • 35 feet * TRACK.SOFT  THEN
 Credible altitude alpha-beta update done here
 TRACK.CREDIBLE = TRUE
```

```
  TRACK.Z = ZPRED + (0.58 * ZDIFF)
  TDIFF = TIN - TRACK.TDAT
  TRACK.ZD = TRACK.ZD + 0.25 * ZDIFF / TDIFF
  TRACK.TDAT = TIN
  TRACK.SOFT = Maximum(2, TRACK.SOFT-1)
ELSE
  Altitude not credible, must reset tracker
  TRACK.Z = ZPD
  TRACK.SOFT = Minimum(10,TRACK.SOFT+1)
  TRACK.credible = FALSE
```

APPENDIX E
NON-REAL-TIME VERTICAL POSITION SMOOTHING ALGORITHM

The vertical tracker algorithms described in Appendix C (for 100-foot flight level altitude inputs) and Appendix D (for 25-foot quantized altitude inputs) are each designed for application in either real-time or non-real-time processing. This appendix will describe a vertical position-smoothing algorithm specifically developed for non real-time processing of recorded radar surveillance data. Intended for the analysis of ACAS encounter scenarios, this algorithm takes as its input an array of altitudes (denoted z[]) and their corresponding measurement times (denoted t[]) for a given aircraft track. The algorithm description here assumes that these arrays are indexed from 1 through N.

The first step of this algorithm is to remove any invalid altitude values. Mode C altitudes that are flagged as garbled or missing are removed from the data arrays. (Note: since the purpose of vertical position smoothing here is to obtain estimates of altitude rate in order to check values reported in the aircraft's Mode S EHS register 60_{16}, only altitudes from Mode S-equipped aircraft will be tracked using this algorithm here. The Mode S surveillance protocols utilize error detection and correction procedures that make the likelihood of missed or garbled altitudes very small.)

The second step of the non real-time vertical tracker algorithm is to remove any outlier altitudes from the data set. Such outlier altitudes may be caused by undetected bit errors in the Mode S protocols, errors in report-to-track correlation, or by problems in the aircraft's avionics. These outliers appear as large jumps in the aircraft's altitude. The outlier testing begins by computing a two-point vertical rate for each data point 1 through N-1 using the following equation.

$$z'_i = \frac{z_{i+1} - z_i}{t_{i+1} - t_i}$$

If the magnitude of the computed vertical rate for a given point i is greater than 5000 feet per minute (an empirically-derived parameter larger than any expected vertical rate for an actual aircraft), then this data point is a candidate altitude outlier. The candidate outlier point whose vertical rate has the largest magnitude is removed from the data set and the vertical rates for the remaining points are computed. (In case of a tie, the earliest-occurring candidate data point is removed.) The search procedure for outlier data points is repeated until no further candidate outlier points are found.

The third step of the non real-time vertical position-smoothing algorithm is to perform a smoothing procedure on the remaining altitude values as defined in the following equation:

$$zsmooth_i = \frac{\sum_j \omega(t_i, t_j) z_i}{\sum_j \omega(t_i, t_j)}$$

The weighting function $\omega(t_i,t_j)$ decreases monotonically as the difference in time between t_i and t_j increases. The following equation defines the weighting function selected. It is a Gaussian kernel with the standard deviation parameter σ. The parameter value of σ=15 seconds was determined empirically (with 100-foot flight level data).

$$\omega(t_i, t_j) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t_i - t_j)^2}{2\sigma^2} \right)$$

The final step of the non real-time vertical position-smoothing algorithm is to compute the vertical rate for each of the remaining data points using the same two-point equation that was used for outlier detection, except that the smoothed values of altitude are used instead of the input values. Vertical rate values can be computed for data points 1 through N-1.

APPENDIX F
RELATIONSHIPS AMONG GROUND SPEED, IAS, TAS, AND MACH

Aviation systems measure speed in a number of different ways. The Mode S Enhanced Surveillance (EHS) application provides four separate speed values in its GICB registers (ground speed and true airspeed in register 50_{16}, indicated airspeed and Mach number in register 60_{16}). This Appendix will describe each of these different speed values and how they are related. The material in this Appendix was derived primarily from reference [10].

The most straightforward aircraft speed measurement is ground speed. This speed is determined by measuring the motion of the aircraft against fixed references (either on the Earth or satellites). The aircraft determines ground speed via GPS, inertial navigation, VOR/DME, or other such onboard navigational systems. This is the speed that a ground Mode S sensor can determine directly from tracked positional measurements, so its value can be directly validated.

Aircraft also measure their speed with respect to the air in which they are flying. There are a number of factors that make this speed differ from the aircraft's ground speed. First of all, the air moves (wind) – and the aircraft move along with it.

Therefore, the airspeed is calculated as the vector difference of the ground speed and the wind speed:

Airspeed = Groundspeed - Windspeed

The ground Mode S sensor has no way to measure the wind field at the location of the aircraft, so it cannot validate airspeeds directly via surveillance data. A second factor is that the atmosphere is not uniform – it varies as a function of altitude and temperature. The density of the atmosphere drops as altitude increases. The air temperature also typically drops as altitude increases. The aviation standard International Standard Atmosphere (ISA) assumes a sea level temperature of 59 degrees F / 15 degrees C and a lapse rate of -3.57 degrees F / 2 degrees C per thousand feet of altitude. The air temperature stabilizes at -69.7 degrees F / -56.5 degrees C at about 36,000 feet. The air temperature then remains stable up to about 65,000 feet. The ground Mode S sensor has no way to measure the air temperature directly – it must be inferred from the measured barometric altitude reported by the aircraft.

There are several types of airspeed values used in aviation. These are:

Indicated Airspeed (IAS): This is the airspeed shown on the pilot's indicator. This is determined onboard by measuring the air pressure produced by the motion of the aircraft through the air.

Calibrated Airspeed (CAS): This is the IAS corrected for errors due to the location of the airspeed pressure sensor(s) of the aircraft. Normally, it does not differ significantly from IAS. For purposes of this appendix, it will be assumed that CAS is equivalent to IAS,

True Airspeed (TAS): This is CAS corrected for instrument installation errors, compressibility errors, and errors due to variations from standard air density (effects of altitude and temperature). TAS is approximately equal to CAS at sea level but increases relative to CAS as altitude increases. For example, at 35,000 feet, 250 knots CAS is approximately 430 knots TAS.

Mach Number (M): The Mach number is defined to be the ratio of the speed of interest to the speed of sound at the given atmospheric condition. The speed of sound can be calculated in units of TAS as a function of aircraft altitude (up to 36,000 feet) using the standard International Standard Atmosphere (ISA) atmospheric assumptions (59 degrees F or 15 degrees C at sea level and a lapse rate of -3.57 degrees F / 2 degrees C per 1000 feet) via the following formula:

Speed of Sound (knots TAS) = $29.06 * \{ 518.7 - (3.57 * A) \}^{0.5}$

where 'A' is the altitude in 1000's of feet. At 36,000 feet, the speed of sound is 573 knots. At sea level, the speed of sound is approximately 661.5 knots assuming ISA conditions,

Figures F-1 and F-2 illustrate the relationships among IAS/CAS, TAS, and M for various altitudes and non-standard temperature conditions. Figure F-1 covers the lower speed range (up to 1000 knots TAS – subsonic speeds) and Figure F-2 covers a higher speed range (600 to 1800 knots TAS – supersonic speeds).

An example case for the use of these relationships is illustrated on Figure F-1. Assume that the IAS corrected to CAS is 370 knots (denoted as point (A) on the figure). Assume that the aircraft is flying at 25,000 feet barometric. Moving horizontally from point (A) to the intersection with the line indicating the aircraft's altitude arrives at the point denoted as (B). To find the value of M, move vertically down to the point denoted (C) at 0.86 Mach. To get the value of TAS in the actual environmental conditions, move from point (B) upwards to the intersection with the sea level reference line (denoted as point (D), then move horizontally to the intersection with the line indicating the actual air temperature (measured in Centigrade units). The example assumes a non-standard value of -20 degrees C – denoted point (E) on the figure. Moving vertically from point (E) gets the TAS for this case (denoted point (F)) – 535 knots. The dashed lines on the figure illustrate how to get the TAS for standard atmospheric conditions – 515 knots. The figure can also be used in reverse to derive CAS from M or TAS.

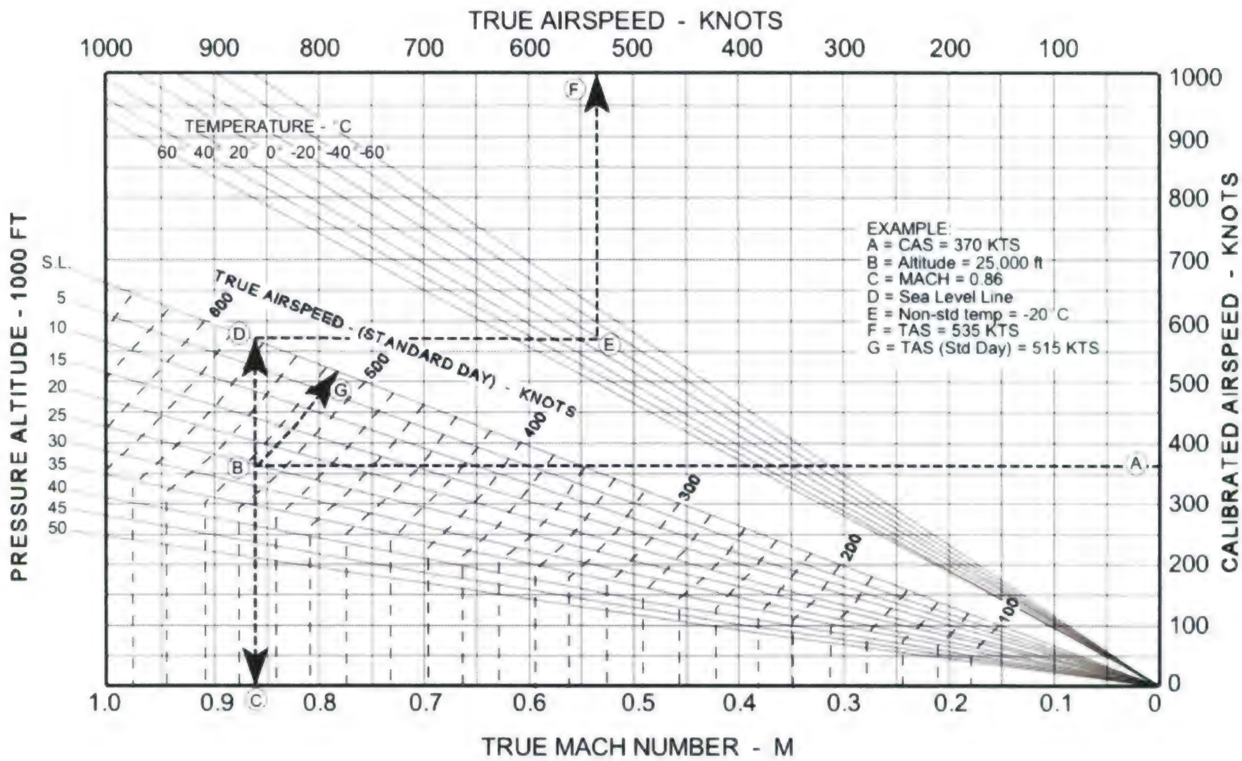


Figure F-1. Relationships Among CAS, TAS, and Mach Numbers for Varying Temperature and Altitude – Subsonic.

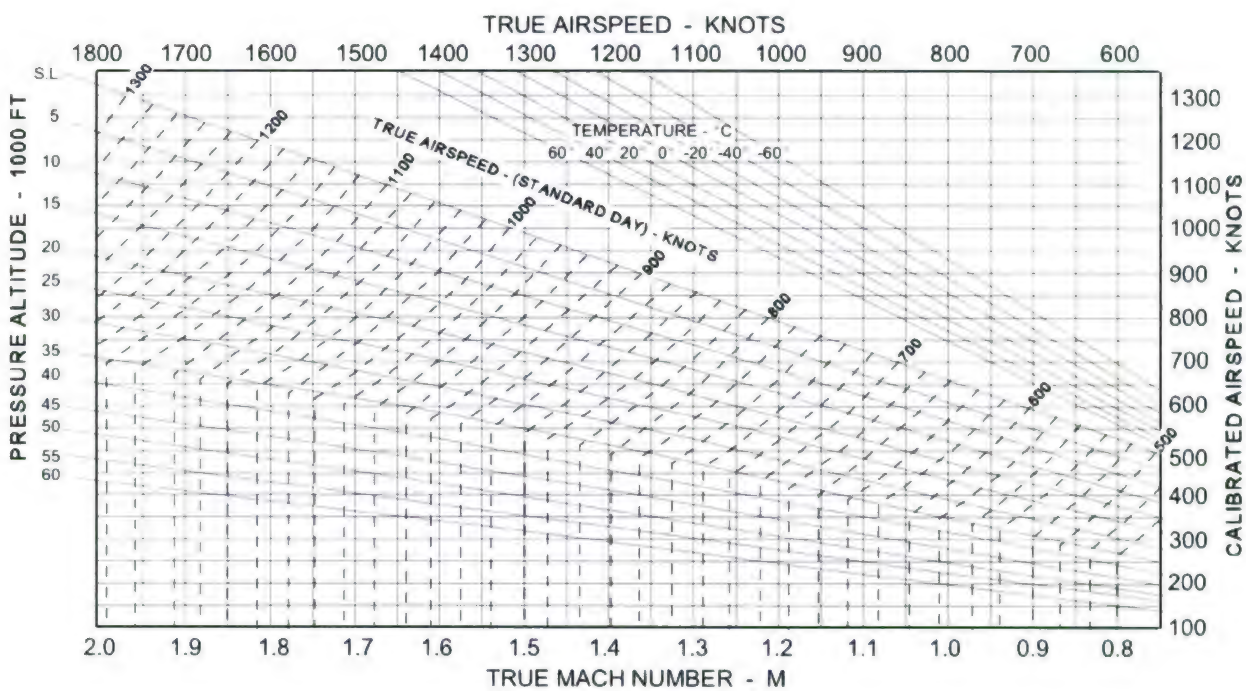


Figure F-2. Relationships Among CAS, TAS, and Mach Numbers for Varying Temperature and Altitude – Supersonic.

The following equations relating CAS, TAS and Mach number were taken from reference [11]. The atmospheric pressure ratio (at actual temperature / at standard temperature) as a function of the aircraft altitude in feet (denoted Lambda) is computed as follows for altitudes less than or equal to 36,000 feet (the pressure ration remains constant between 36,000 feet and 65,000 feet):

$$\text{Lambda} = (1 - 0.0000068753 * \text{altitude})^{5.2561}$$

The following procedure computes the relationship between the aircraft's CAS (in knots) and its Mach number:

$$T_1 = 1 + 0.2 * (\text{CAS} / 661.5)^2$$

$$T_2 = (T_1)^{3.5} - 1$$

$$T_3 = (1/\text{Lambda}) * (T_2 + 1)$$

$$T_4 = (T_3)^{0.286} + 1$$

$$\text{Mach} = (T_4)^{0.5}$$

Note that the speed of sound in ISA conditions at sea level is 661.5 knots. Defining the atmospheric temperature ratio (actual temperature / standard temperature) as theta (temperatures in degrees Centigrade), the relationship between the aircraft's Mach number and its TAS (in knots) is given by:

$$\text{TAS} = 661.5 * \text{Mach} * (\text{theta})^{0.5}$$

The temperature ration can be modeled using the ISA standard model for the atmospheric temperature lapse rate as a function of altitude described previously in this appendix. Alternatively, if the aircraft's measured air temperature and pressure is available (see Appendix G), then lambda and theta can be calculated directly.

APPENDIX G
THE MODE S METEOROLOGICAL AIR REPORT (REGISTER 44_{16})

As was discussed in Appendix F, the conversion between indicated airspeed and true airspeed involves having the local value of air temperature. While this value can be approximated using ISA standard day rules, it would be better to have the actual measured value. Also, the full validation of airspeed and heading values for EHS requires having the local wind speed and direction data from the aircraft's location. The wind information can only be crudely approximated with Mode S ground sensor surveillance data.

While it is not a part of the ELS/EHS application definition of Mode S, a transponder register is defined (see [2]) to provide aircraft-measured meteorological data. As shown in Figure G-1, extraction of this register can provide the values of wind speed/direction and air temperature required to validate the EHS data. Note: if the input surveillance source provides ASTERIX Category 048 target reports, then the contents of the extracted register 44_{16} are available in Data Item 250 as described in Figure 1-2 of this report.

The following configuration tests are required to determine if the aircraft's avionics are supporting the meteorological report (register 44_{16}). These tests are in addition to the ELS/EHS configuration tests described in section 2 of this report:

Bit 13 of register 17_{16} set (see Figure A-2); and

Bit 45 of register 19_{16} set (see Figure A-4).

If both of these configuration bits are set, then the aircraft supports the routine meteorological report (register 44_{16}).

If the status bit for winds and temperature data (bit 5) of register 44_{16} is set, then the wind speed in knots (0...511) is extracted from bits 6 through 14. The wind direction in degrees with respect to geographic north (0...360) is extracted from bits 15 through 23. The LSB for wind direction is $360/2^9$, about 0.7 degrees. Note that the wind direction in register 44_{16} is an unsigned vale measured clockwise from north – not a signed value like the EHS true track angle (in register 50_{16}) and magnetic heading (in register 60_{16}). The airspeed is computed as the vector sum of the ground speed (measured via the surveillance radar) and the wind speed extracted from the meteorological data. The air temperature in degrees C (-128...+128) is extracted from register 44_{16} as follows:

(1) Extract bit 24 as SIGN

(2) Extract bits 25 through 34 as VAL

(3) If SIGN=1, then VAL = VAL – 2^{10}

(4) Air Temperature (degrees C) = VAL / 2^{10}

The LSB of the extracted temperature data is 0.25 degrees C. It should be noted that the aircraft actually computes the wind data onboard by comparing its source of navigation data (e.g., GPS, INS) with its source of air-relative data (airspeed and heading).

MB FIELD

Bit	Field
1–4	RESERVED
5	STATUS
6	MSB = 256 knots
7–13	WIND SPEED Range = [0, 511] knots
14	LSB = 1 knot
15	STATUS
16	MSB = 180 degrees
17–22	WIND DIRECTION (True) Range = [0, 360] degrees
23	LSB = 180/128 degrees
24	STATUS
25	SIGN
26	MSB = 64°C
27–34	STATIC AIR TEMPERATURE Range = [-128, +128] °C
35	LSB = 0.125° C
36	STATUS
37	MSB = 1 024 hPa
38–46	AVERAGE STATIC PRESSURE Range = [0, 2 047] hPa
47	LSB = 1 hPa
48	TURBULENCE FLAG
49	STATUS
50	MSB = 64%
51–55	HUMIDITY Range = [0, 127] %
56	LSB = 1 %

PURPOSE: To allow meteorological data to be collected by ground systems.

1) The definition of bit 48: Turbulence flag:

0 = signifies turbulence data not available in Register 45_{16}.
1 = signifies turbulence data available in Register 45_{16}.

Note 1. *The average static pressure is not a requirement of Annex 3.*

Note 2. *Humidity calculation may result in values greater than 100 %.*

Note 3. *Two's complement coding is used for all signed fields as specified in §A.2.2.2.*

Note 4. – *The requirement for the range of wind speeds in Annex 3 is from 0 to 250 knots.*

Note 5. – *The requirement for the range of static air temperature in Annex 3 is from -80° C to +60° C.*

Figure G-1. Routine Meteorological Report (BDS Code 4,4).

APPENDIX H
THE FAA'S TERMINAL MODE S SENSOR COMMUNICATIONS INTERFACE DESIGN

The Mode S sensors specified in [6] and fielded by the FAA in terminal areas across the U.S. do not support the ASTERIX formats (specified in [5]). Instead, these sensors employ a combination of the Common Digitizer (CD-2) surveillance output specified in [14] and the communications interface specified in [13]. This Appendix will discuss the techniques and methods required to employ these sensors for ELS and EHS validation.

The FAA's terminal Mode S sensors provide their surveillance output to ATC applications using the CD-2 format. While this surveillance output is sufficient to drive controller's displays, it lacks several key data items necessary for ELS/EHS validation. In particular, CD-2 format does not provide the Mode S address for Mode S-equipped aircraft. Even if the address for the desired aircraft is known prior to testing, there is no direct way to match the CD-2 surveillance data with the address. CD-2 data does not provide a track number either. The aircraft's Mode 3/A (ATCRBS) code is the only means to locate a particular aircraft in the CD-2 data stream – assuming that the aircraft has been assigned a discrete (known) Mode 3/A code. Unlike ASTERIX format, CD-2 provides no mechanism for transmitting the contents of Mode S transponder registers. Hence, the CD-2 surveillance data stream is not useful for ELS/EHS validation application.

The FAA's terminal Mode S sensor communications interface, however, can provide the necessary surveillance data items and control functions for ELS/EHS validation. This Appendix will discuss the subset of the communications interface functionality used for this application. The material in this Appendix is derived from [13].

H.1 Link-Level Protocols

The Mode S communications interface operates over a point-to-point, bidirectional, synchronous, bit-serial link layer as specified in the CCITT X.25 LAPB standard ([15]). The Mode S sensor operates as a Data Terminal Equipment (DTE) port under the X.25 protocol. A single sensor can handle multiple communication interfaces; each communications interface may be separately configured. The ELS/EHS validation application operates as an X.25 Data Circuit Terminating Equipment (DCE).

Each Mode S message is transferred in an X.25 data frame. Each frame starts and ends with a flag sequence. Addressing and control information in the frame header specify the source and destination of each frame, as well as whether the frame contains user data or link control functions. Frame numbering in the control information provides for detection of out-of-sequence or lost frames. Each frame incorporates a frame-check sequence that is used to detect frames containing bit errors. A zero-insertion algorithm is used to provide unambiguous detection of the flag sequences. Exception and recovery processing is defined by the X.25 standard to deal with the various link-level error conditions. As implemented in Mode S, the largest data frame

contains 1024 bytes. (The longest data frame of the subset of messages to be used for ELS/EHS validation is only 22 bytes.)

H.2 Communications Interface Messages

An FAA terminal sensor can support multiple communications interfaces. (Note: none of these interfaces are currently connected in the NAS.) Each communications interface may be operated in one of two modes as selected by a sensor configuration parameter. If the user of the communications interface is a normal ATC facility also receiving surveillance data via the CD-2 interface, then the communications interface is operated in the ATC mode. However, as discussed above in this appendix, CD-2 surveillance data is not appropriate for the ELS/EHS validation task. For ELS/EHS validation, the communications interface should be operated in the non-ATC mode. As will be discussed below, this mode provides for both surveillance (of Mode S-equipped aircraft only) and communications data (e.g., the extraction of GICB registers from an aircraft equipped with a Mode S transponder) to share the single interface with the sensor. The surveillance data available in the non-ATC mode does contain the data items required for ELS/EHS validation. The remainder of this appendix will only consider those messages and protocols supported by the non-ATC mode of the communications interface.

H.2.1 Common Data Fields in non-ATC Communications Messages

This section will describe the commonly used data items in non-ATC mode messages employed over the Mode S communications interface. Data items particular to a specific message will be described with the message itself.

H.2.1.1 Sensor Identifier

The sensor identifier is a 10-bit number that uniquely specifies the sensor generating the message. This functionality was added to permit multi-sensor networking, and it is not required for any currently fielded application.

H.2.1.2 Message Number

Each message over the communications interface is given a unique 8-bit identifying number. Messages output from the sensor to the user (e.g., ELS/EHS validation) use the range of numbers 129 through 255, while messages received by the sensor from the user use the range of numbers 1 through 127. Message numbers 0 and 128 are reserved. The message number 128 is typically used for broadcast messages. The message numbers are used to match user data requests with sensor responses. The numbers should be assigned sequentially at each end of the communications interface (from the appropriate range of numbers). Up to 127 outstanding messages in each direction can be handled by the communications interface protocol.

H.2.1.3 Padding Bits

In order to align certain fields of the message on byte boundaries for coding efficiency, the message formats sometimes employ padding bits. These bits are always cleared to zero.

H.2.1.4 Type Code

The first byte of each communications interface message is a type code that identifies the particular message. Table H-1 defines the subset of non-ATC mode message type codes used for ELS/EHS validation. The term downlink in this table refers to messages (responses) coming from the aircraft through the sensor interface to the user (e.g., ELS/EHS validation). The term uplink refers to messages (requests) coming from the user through the sensor interface and sent up to the aircraft. The type code values are expressed in hexadecimal notation.

Table H-1
Non-ATC Message Type Codes (subset for ELS/EHS)

Category	Type Code	Message Type
Sensor Error Response	31_{16}	Message Rejection/Delay Notice
Downlink	34_{16}	Data Link Capability Response
	40_{16}	Broadcast Downlink
	44_{16}	GICB Downlink Response
	45_{16}	ATCRBS Mode 3/A Code Response
	48_{16}	Broadcast Downlink with Position
	$4C_{16}$	GICB Downlink Response with Position
	$4F_{16}$	Aircraft Position Response
Uplink	09_{16}	Aircraft Position Request
	$0A_{16}$	Data Link Capability Request
	24_{16}	ATCRBS Mode 3/A Code Request
	$2B_{16}$	GICB Downlink Request
Sensor Status	$4B_{16}$	Track Drop Message

H.2.2 Request-Response Messages

Most of the non-ATC messages on the communications interface follow a request-response protocol – the user sends a request message to the Mode S sensor asking for a particular item of aircraft data from a specific aircraft. Some time later, the sensor responds with a message containing the requested data. The set of request-response message pairs used by the ELS/EHS validation function will be described below. (Note: the broadcast downlink message with/without position (Section H.2.2.5) is not elicited by a user request. The Data Link Capability Response message (Section H.2.2.2) is also generated without requiring a user request when an aircraft is newly-acquired by a Mode S sensor.)

If the sensor cannot fulfill the user's request (e.g., aircraft not in sensor's database, request message format incorrect), then a message rejection/delay message is sent instead of the expected response. Table H-2 illustrates the format of this error status message.

Table H-2
Format of Message Rejection/Delay Notice

Data Field	Number of Bits	Commentary
Type Code	8	31_{16}
Mode S Address	24	Address from request
Message Number	8	Number from request
Qualifier	3	0 = target not in data base, 1= target not yet in roll-call, 2 = too many messages, 3 = sensor not primary, 4 = no ELM support, 5..7 unassigned
Padding Bits	3	000
Sensor Identifier	10	Supporting Sensor

H.2.2.1 ATCRBS Mode 3/A Request-Response

The format for the ATCRBS Mode 3/A request message is illustrated in Table H-3(A). (Note: this data can only be obtained for Mode S-equipped aircraft in the sensor's coverage.) The format for the matching response message is illustrated in Table H-3(B). The ATCRBS Mode 3/A code consists of 12 bits expressed as 4 octal digits.

Table H-3(a)
Format of ATCRBS Mode 3/A Request Message

Data Field	Number of Bits	Commentary
Type Code	8	24_{16}
Mode S Address	24	Request Address
Message Number	8	Request Message Number

Table H-3(b)
Format of ATCRBS Mode 3/A Response Message.

Data Field	Number of Bits	Commentary
Type Code	8	45_{16}
Mode S Address	24	Address from Request
Message Number	8	Response Message Number
Padding Bits	4	0000
ATCRBS Mode 3/A Code	12	4 octal digits
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

H.2.2.2 Data Link Capability Request-Response

The format for the Data Link Capability request message is illustrated in Table H-4(A). The format for the matching response message is illustrated in Table H-4(B). (Note: this data can only be obtained for Mode S-equipped aircraft in the sensor's coverage.) The Data Link

Capability response returns the 3-bit value of the aircraft transponder's CA field (see Section 2.1). It also returns the low-order 52 bits of the aircraft's data link capability register (10_{16}) contents termed the extended capability (see A-1 for the format of this register). The first 4 bits of the register contents are a constant value, so nothing is lost by omitting them. For ELS/EHS testing, the first four bits of the capability data should be reset to the value 1.

Table H-4(a)
Format of Data Link Capability Request Message

Data Field	Number of Bits	Commentary
Type Code	8	$0A_{16}$
Mode S Address	24	Request Address
Message Number	8	Request Message Number

Table H-4(b)
Format of Data Link Capability Response Message

Data Field	Number of Bits	Commentary
Type Code	8	34_{16}
Mode S Address	24	Address from Request
Message Number	8	Response Message Number
Padding Bit	1	0
Transponder CA Value	3	See section 2.1
Transponder Extended Capability Value	52	Low-order 52 bits of transponder register 10_{16}
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

H.2.2.3 Aircraft Position Request-Response

The format for the Aircraft Position request message is illustrated in Table H-5(A). (Note: position data can only be obtained for Mode S-equipped aircraft in the sensor's coverage.) The format for the matching response message is illustrated in Table H-5(B). The response message contains the aircraft's position (range, azimuth, altitude) as well as the horizontal velocity components (range-rate, azimuth-rate). Note that the LSBs for the range and azimuth position values are larger than the raw sensor – the measurement sigma values need to be adjusted accordingly. The velocity values in the response message are computed using a 2-point interpolator, so they are likely to be quite noisy and some form of smoothing algorithm should be used before applying these velocity values for ELS/EHS validation purposes. Also, note that terminal sensors are typically calibrated in azimuth with respect to magnetic north at the sensor.

Table H-5(a)
Format of Aircraft Position Request Message

Data Field	Number of Bits	Commentary
Type Code	8	09_{16}
Mode S Address	24	Request Address
Message Number	8	Request Message Number

Table H-5(b)
Format of Aircraft Position Response Message

Data Field	Number of Bits	Commentary
Type Code	8	$4F_{16}$
Mode S Address	24	Address from Request
Message Number	8	Response Message Number
Padding Bits	2	00
Range	10	0..255 nautical miles, LSB=1/4 mile
Azimuth	12	0..360 degrees, LSB=$360/2^{12}$ (~0.088 deg.)
Padding Bits	2	00
Range Rate	6	Nautical miles/second, LSB=0.0125 (~45 knots), MSB=0.2 (~720 knots)
Azimuth Rate	8	Degrees/second, LSB=0.031, MSB=2
Aircraft State	4	0=aircraft not in sensor data base, 1=aircraft not in roll-call yet, 2=full track, sensor controlled primary, 3=full track, controlled secondary, 4=full track, uncontrolled primary, 5=full track, uncontrolled secondary, 6..15 unassigned NOTE: values 2..5 are equivalent for ELS/EHS validation
Altitude	12	Mode C altitude of aircraft in Gray code bits (Q bit determines 100-foot or 25-foot encoding)
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

H.2.2.4 GICB Downlink Request-Response

The format for the GICB Downlink request message is illustrated in Table H-6(A). The format for the matching response message is illustrated in Table H-6(B). A new request is required for each transponder register extraction desired.

A priority value from 0 (lowest priority) to 15 (highest priority) is included in the request message. If there is a queue of messages waiting for a particular aircraft, the messages will be sent in priority order. The only Mode S data link application currently operating in terminal sensors, TIS, uses priority 10. Hence, a lower priority is suggested for ELS/EHS validation requests in order to avoid conflicting with the TIS application.

Each request is given a maximum number of sensor scans in which to complete (before a rejection notice will be sent to the user). The coding of the expiration value is given in the table H-6(B) commentary. To avoid overloading the sensor, an expiration value of no more than 2 scans is recommended.

Table H-6(a)
Format of GICB Downlink Request Message

Data Field	Number of Bits	Commentary
Type Code	8	$2B_{16}$
Mode S Address	24	Request Address
Message Number	8	Request Message Number
Priority	4	Suggested value=8
Expiration	3	0=1 scan, 7=no expiration, 1..6= $2^{(exp-1)}$ scans
Padding Bit	1	0
Register BDS Code	8	Desired Transponder Register

Table H-6(b)
Format of GICB Downlink Response Message

Data Field	Number of Bits	Commentary
Type Code	8	44_{16}
Mode S Address	24	Address from Request
Message Number	8	Response Message Number
Register BDS Code	8	Requested transponder register
Register Contents	56	Extracted Register Contents
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

It should be noted that a GICB Downlink response message can be combined with an Aircraft Position response if the sensor's communication interface configuration parameters for this port are set up for this function. (Note: position data can only be obtained for Mode S-equipped aircraft in the sensor's coverage.) There is a trade-off between the extra bits required on the communications link (since every GICB downlink and broadcast downlink message will have the extra position fields appended) versus not requiring a separate aircraft position request message for each aircraft (and potential positional latency issues). Table H-6(C) illustrates the format of the GICB Downlink with Position Response Message.

Table H-6(c)
Format of GICB Downlink with Position Response Message

Data Field	Number of Bits	Commentary
Type Code	8	$4C_{16}$
Mode S Address	24	Address from Request
Message Number	8	Response Message Number
Register BDS Code	8	Requested transponder register
Register Contents	56	Extracted Register Contents
Padding Bits	2	00
Range	10	0..255 nautical miles, LSB=1/4 mile
Azimuth	12	0..360 degrees, LSB=$360/2^{12}$ (~0.088 deg.)
Padding Bits	2	00
Range Rate	6	Nautical miles/second, LSB=0.0125 (~45 knots), MSB=0.2 (~720 knots)
Azimuth Rate	8	Degrees/second, LSB=0.031, MSB=2
Aircraft State	4	0=aircraft not in sensor database, 1=aircraft not in roll-call yet, 2=full track, controlled primary, 3=full track, controlled secondary, 4=full track, uncontrolled primary, 5=full track, uncontrolled secondary, 6..15 unassigned NOTE: values 2..5 are equivalent for ELS/EHS validation
Altitude	12	Mode C altitude of aircraft in Gray code bits (Q bit determines 100-foot or 25-foot encoding)
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

H.2.2.5 Broadcast Downlink

The format for the Broadcast Downlink message is illustrated in Table H-7(A). These messages result from transponder broadcasts and are not the result of a request message. Note that the first 8 bits of the broadcast data contain the register identifier (BDS code).

Table H-7(a)
Format of Broadcast Downlink Message

Data Field	Number of Bits	Commentary
Type Code	8	40_{16}
Mode S Address	24	Address from Request
Message Number	8	Message Number = 128
Register Contents	56	Broadcast Register Contents
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

It should be noted that a Broadcast Downlink message can be combined with an Aircraft Position response if the sensor communications interface configuration parameters for this port are set up for this function. (Note: position data can only be obtained for Mode S-equipped aircraft in the sensor's coverage.) There is a trade-off between the extra bits required on the communications link (since every GICB downlink and broadcast downlink message will have the extra position fields appended) versus not requiring a separate aircraft position request message for each aircraft (and potential positional latency issues). Table H-7(B) illustrates the format of the GICB Downlink with Position Response Message.

Table H-7(b)
Format of Broadcast Downlink with Position Response Message

Data Field	Number of Bits	Commentary
Type Code	8	48_{16}
Mode S Address	24	Address from Request
Message Number	8	Message Number = 128
Register Contents	56	Extracted Register Contents
Padding Bits	6	000000
Range	10	0..255 nautical miles, LSB=1/4 mile
Azimuth	12	0..360 degrees, LSB=$360/2^{12}$ (~0.088 deg.)
Padding Bits	2	00
Range Rate	6	Nautical miles/second, LSB=0.0125 (~45 knots), MSB=0.2 (~720 knots)
Azimuth Rate	8	Degrees/second, LSB=0.031, MSB=2
Aircraft State	4	0=aircraft not in sensor database, 1=aircraft not in roll-call yet, 2=full track, controlled primary, 3=full track, controlled secondary, 4=full track, uncontrolled primary, 5=full track, uncontrolled secondary, 6..15 unassigned NOTE: values 2..5 are equivalent for ELS/EHS validation
Altitude	12	Mode C altitude of aircraft in Gray code bits
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

H.2.2.6 Determination of Mode S Addresses

To this point, the discussion of the Mode S communications interface protocols has assumed that the user's application knows the aircraft's Mode S address prior to making any data requests to it. This section will describe the process by which the user's application (e.g., ELS/EHS validation) determines the Mode S addresses of the aircraft currently in coverage of the Mode S sensor supporting the interface.

Whenever a new Mode S-equipped aircraft is acquired by the sensor and placed under roll-call track, a Data Link Capability Response message (see Table H-4(B)) is spontaneously transmitted (without requiring a request input) from the sensor on the communications interface. The message number for this message will be 128 – the default value. The user's application should monitor these messages, adding the Mode S address from these messages to its list of aircraft available for subsequent data requests.

The Mode S communications interface protocol will attempt to deliver messages to an aircraft regardless of whether the aircraft is properly equipped to respond to them. These unanswered uplinks interfere with the operation of the sensor and should be avoided. Hence, the user application should check the aircraft's Mode S data link capabilities prior to requesting any data other than the ATCRBS Mode 3/A code (H.2.2.1) or the Aircraft Position (H.2.2.3). In particular, the GICB Downlink Request message (H.2.2.4) should not be generated for an aircraft whose Mode S transponder CA value is less than 4.

The Mode S sensor generates a Track Drop message on the communications interface to indicate that a particular aircraft has left sensor coverage. Table H-8 illustrates the format of the Track Drop Message. The message includes the sensor identifiers for two adjacent sensors (secondary and tertiary) as well as the supporting sensor. This mechanism was intended to support sensor networking, but is not operational in the FAA's fielded Mode S sensors.

Table H-8
Format of Track Drop Message

Data Field	Number of Bits	Commentary
Type Code	8	$4B_{16}$
Mode S Address	24	Address from Request
Message Number	8	Message Number
Padding Bits	6	000000
Sensor Identifier	10	Secondary sensor
Padding Bits	6	000000
Sensor Identifier	10	Tertiary sensor
Padding Bits	6	000000
Sensor Identifier	10	Supporting Sensor

APPENDIX I
THE ASTERIX CATEGORY 018 SURVEILLANCE AND DATA LINK INTERFACE

The ASTERIX Category 018 interface function provides bi-directional surveillance and Mode S data link communications between Mode S sensors and applications such as ELS/EHS monitoring and validation. ASTERIX Category 018 provides an internationally standardized equivalent functionality to the FAA's communications interface that was described in Appendix H. This appendix will describe the subset of ASTERIX Category 018 functionality that would be used for ELS/EHS monitoring and validation applications. See [16] for the complete definition of ASTERIX Category 018 formats and protocols.

I.1 Common Data Items

All the ASTERIX Category 018 messages used for ELS/EHS monitoring and validation applications have four common data items. These data items common to all messages will be described in this section. Those data items specific to a given message type will be described with that particular message. A summary of all the ASTERIX Category 018 Data Items described in this appendix is given in Table I-7 (see Section I.5).

I.1.1 Message Type

The Message Type (Data Item 000) is a one-byte value that identifies the type of the ASTERIX Category 018 message. Table I-1 defines the message type encodings used for the subset of ASTERIX Category 018 messages used for ELS/EHS monitoring and validation applications. The message type coding values in Table I-1 are given in hexadecimal notation. See [15] for the complete list of ASTERIX Category 018 message type values.

Table I-1
ASTERIX Category 018 Message Type Encodings

Message Type	Encoding	Section Reference
Request Aircraft Report	11_{16}	H.2.1
Aircraft Report Response	10_{16}	H.2.2
Request GICB Extraction	40_{16}	H.3.1
GICB Extraction Response	43_{16}	H.3.2
GICB Extraction Acknowledgement	42_{16}	H.3.3
Cancel GICB Extraction	41_{16}	H.3.4
Downlink Broadcast	34_{16}	H.4

I.1.2 Mode S Address

The Mode S Address (Data Item 005) contains the address of the aircraft that is the source of, or the destination for, this particular message. The address field consists of 3 bytes (24 bits).

I.1.3 Data Source Identifier

The data source identifier (Data Item 036) provides the identification of the message source. For uplinks, this would be the identification of the ELS/EHS monitor. For downlinks, this would be the identification of the Mode S sensor supporting the ELS/EHS monitoring and validation application.

The data source identifier consists of two bytes. The high-order byte is the system area code (SAC) that denotes that geographic region in which the data source resides. (See [17] for the standard SAC encodings.) The low-order byte is the system identity code (SIC) that specifies the particular system within the geographic region. SIC values are defined by the agency that controls the geographic region of the particular SAC value.

I.1.4 Data Destination Identifier

The data destination identifier (Data Item 037) provides the identification of the message destination. For downlinks, this would be the identification of the ELS/EHS monitor. For uplinks, this would be the identification of the Mode S sensor supporting the ELS/EHS monitoring and validation application.

The data destination identifier consists of two bytes. The encoding of the data destination identifier is generated in an equivalent manner to the data source identifier described in I.1.3 (one byte SAC and one byte SIC).

I.2 Aircraft Report (Surveillance Data)

ASTERIX Category 018 provides a request-response protocol that allows an application to obtain a significant portion of the database maintained by a Mode S sensor about a specific aircraft in coverage. Some of this data parallels the sensor surveillance outputs available in ASTERIX Category 048 (see [5]) that was described in previous sections of this report.

I.2.1 Aircraft Report Request

The ASTERIX Category 018 request message for an aircraft report (message type 11_{16}) contains two additional data items beyond the common ones described in I.1. These two data items provide a way to tailor the request to limit the aircraft data in the response to only what is required by the application generating the request. This appendix will only consider those elements useful for ELS/EHS monitoring and validation. (See [16] for the complete definition of the aircraft report request/response messages.)

I.2.1.1 Aircraft Data Link Command

The ASTERIX Category 018 Aircraft Data Link Command (Data Item 007) provides a means for the application to enable or disable data link communications flows to or from a specific aircraft. Data Item 007 consists of one byte. The high-order four bits of the byte are used as Boolean flags, and the low-order bits are reserved and should be set to zero. The ELS/EHS monitoring and validation function utilizes both uplink and downlink data flows, so

both should be enabled at all times for aircraft of interest. Hence, the default value for this data item for ELS/EHS monitoring and validation applications should be $F0_{16}$ (all flag bits are set).

I.2.1.2 Aircraft Data Link Report Request

The ASTERIX Category 018 Aircraft Data Link Report Request (Data Item 009) provides a means to tailor the particular request to include only the items of interest to the requestor. Data Item 009 consists of a one required byte with a second extension byte if necessary. Each byte is composed of a series of Boolean flag bits – each flag bit indicates the desired response for a particular piece of data about the aircraft. Setting a flag bit to 1 indicates that the particular data is to be included in the response. The low-order bit of each byte of Data Item 009 flags whether an extension byte is required or not. The ELS/EHS monitoring and validation application will require data flags in both bytes of Data Item 009, so the extension bit is set in the first byte and cleared in the second byte. Only those flag bits corresponding to data useful in the ELS/EHS monitoring and validation application will be described here. (See [15] for the complete definition of Data Item 009.)

Table I-2(a) describes the flag bits in the first byte of Data Item 009, while Table I-2(b) describes the flag bits in the second byte of Data Item 009. The not applicable indication is used for data that is not useful for the ELS/EHS monitoring and validation application. Further information about the data elements used for ELS/EHS monitoring and validation will be discussed as part of the Aircraft Data Link Response message in Section I.2.2.

Table I-2(a)
ASTERIX Category 018 Data Item 009 (Byte 1)

Bit Number	Description	Equivalent Data Item in ASTERIX Category 048
8	Not applicable	--
7	Transponder Capability (CA)	230
6	Transponder Extended Capability (Register 10_{16} contents)	--
5	Aircraft Coverage Quality Factor (Flight Status)	230
4	Not applicable	--
3	Aircraft Position in Polar Coordinates	040
2	Aircraft Position in Cartesian Coordinates	042
1	Extension to second byte (=1)	--

Table I-2(b)
ASTERIX Category 018 Data Item 009 (Optional Byte 2)

Bit Number	Description	Equivalent Data Item in ASTERIX Category 048
8	Aircraft Identification	240
7	Mode 3/A Code	080
6	Aircraft Ground Speed	200
5	Aircraft Altitude	100
4	Aircraft Ground Track Angle	200
3	Reserved (=0)	--
2	Reserved (=0)	--
1	Extension to second byte (=0)	--

I.2.2 Aircraft Data Link Report Response

The Mode S sensor generates an Aircraft Data Link Report response message (message type 10_{16}) in response to a request message (Section I.2.1). In addition to the common data items described in Section I.1, the response message contains an indication of aircraft data link status and zero or more additional items as requested. Those response items applicable to the ELS/EHS monitoring and validation application will be described here. (See [16] for the complete definition of the ASTERIX Category 018 Aircraft Data Link Response message.)

I.2.2.1 Aircraft Data Link Status

The ASTERIX Category 018 Aircraft Data Link Status (Data Item 008) consists of a one required byte with a second extension byte if necessary. Each byte is composed of a series of Boolean flag bits. The low-order bit of each byte of Data Item 008 flags whether an extension byte is required or not. Tables I-3(a) describes the flag bits in the first byte of Data Item 008, while Table I-3(b) describes the flag bits in the second (optional) byte of Data Item 008.

Note in particular bit 2 of the first byte of Data Item 008. When this bit is set, it indicates that the particular aircraft in the request is no longer in the coverage of the Mode S sensor receiving the request. This is one mechanism that an application using ASTERIX Category 018 can determine that an aircraft track has been dropped. ASTERIX Category 018 does not provide a track drop message equivalent to that described in Table H-8.

Table I-3(a)
ASTERIX Category 018 Data Item 008 (Byte 1)

Bit Number	Description	Values
8	Uplink Data Frames	0=enabled, 1=disabled
7	Extract Uplink Frames	0=enabled, 1=disabled
6	Current Uplink Status	0=enabled, 1=disabled
5	Current Downlink Status	0=enabled, 1=disabled
4	Reserved	0
3	Reserved	0
2	Aircraft in Sensor Coverage	0=in coverage, 1=out of coverage
1	Extend to Second Byte	0=no extension, 1=extension

Table I-3(b)
ASTERIX Category 018 Data Item 008 (Optional Byte 2)

Bit Number	Description	Values
8	Uplink/Downlink Changeable via Data Link Command	0=enabled, 1=disabled
7	Reserved	0
6	Reserved	0
5	Reserved	0
4	Reserved	0
3	Reserved	0
2	Reserved	0
1	Extend	0

I.2.2.2 Transponder Capability

If bit 7 in the first byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(a)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 010. This one-byte field contains the transponder capability (CA) field for the specified aircraft. (See Section 2.1 of this report for the use of the CA value in ELS/EHS monitoring and validation applications.)

I.2.2.3 Transponder Extended Capability Report

If bit 6 in the first byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(a)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 011. This seven-byte field contains the 56-bit contents extracted from the aircraft Mode S transponder's Data Link Capability Report (register 10_{16}). (See Section 2.4 for the use of the extended capability report in ELS/EHS monitoring and validation applications.)

I.2.2.4 Aircraft Position in Polar Coordinates

If bit 3 in the first byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(a)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 014. This data is equivalent to ASTERIX Category 048 Data Item 040. The first 16 bits of the data item contains the slant range with an LSB of $1/256^{th}$ of a nautical mile. The second 16-bits of the data item contains the aircraft azimuth measured with respect to geographic north. The LSB of the azimuth is $360/2^{16}$ (about 0.0055 degrees).

I.2.2.5 Aircraft Position in Cartesian Coordinates

If bit 2 in the first byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(a)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 015. This data is equivalent to ASTERIX Category 048 Data Item 042. The first 16 bits of the data item contains the signed x-axis position with an LSB of $1/256^{th}$ of a nautical mile. The second 16-bits of the data item contains the signed y-axis position. Negative values are expressed in 2's-complement form.

I.2.2.6 Aircraft Identification

If bit 8 in the optional second byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(b)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 031. This data is equivalent to ASTERIX Category 048 Data Item 240. The seven bytes of this data item contain the 56-bit contents of the Mode S transponder's Aircraft Identification (register 20_{16}). (See Section 5 of this report for the use of the Aircraft Identification in ELS/EHS monitoring and validation.)

I.2.2.7 Aircraft Mode 3/A Identity Code

If bit 7 in the optional second byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(b)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 032. This data is equivalent to ASTERIX Category 048 Data Item 070. The two bytes of this data item contain the 12-bit contents of the Mode S transponder's reported Mode 3/A identity code. (See Section 4 for the use of the Aircraft Mode 3/A Identity Code in ELS/EHS monitoring and validation.)

I.2.2.8 Aircraft Altitude

If bit 5 in the optional second byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(b)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 100. This data is equivalent to ASTERIX Category 048 Data Item 090. The two bytes of this data item contain the 14-bit contents of the Mode S transponder's reported Mode C altitude. The LSB of the altitude is 25 feet, regardless of whether the aircraft reports in 25 or 100-foot quantization.

I.2.2.9 Aircraft Speed

If bit 6 in the optional second byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(b)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 034. This data is also contained in ASTERIX Category 048 Data Item 200. The two bytes of this data item contain the tracked ground speed of the aircraft. The LSB of the ground speed value is 2^{-14} knots (about 0.22 knots).

I.2.2.10 Aircraft Ground Track Angle

If bit 4 in the optional second byte of Data Item 009 of the Aircraft Data Link Report request (see Table I-2(b)) was set to 1, then the response will contain ASTERIX Category 018 Data Item 035. This data is also contained in ASTERIX Category 048 Data Item 200. The two bytes of this data item contain the ground track angle of the aircraft measured with respect to geographic north. The LSB of the track angle value is $360/2^{16}$ degrees (about 0.0055 degrees).

I.3 GICB Extraction (Data Link)

ASTERIX Category 018 provides a request-response protocol that allows an application (e.g., ELS/EHS monitoring and validation) to obtain the contents of selected aircraft GICB registers. This protocol is similar in function to the FAA's Mode S sensor communication interface described in Appendix H.

The ASTERIX Category 018 protocol not only provides a single request-response protocol, but it also provides a means for a single request to generate periodic extractions of a given register from a given aircraft with a selectable update period. A periodic request repeats until it is (1) cancelled by a GICB Extraction Cancellation (see I.3.4), or (2) the extraction request fails (e.g., the selected aircraft has flown out of the sensor coverage).

Each of the ASTERIX Category 018 GICB extraction protocol messages includes the common data items described in I.1. In addition, each of the GICB extraction messages includes a 32-bit GICB number (Data Item 025). This GICB number provides the means to match up the application's request with the Mode S sensor's later responses. The application should increment the GICB number for each request it makes.

I.3.1 GICB Extraction Request

The ASTERIX Category 018 GICB Extraction Request message (message type 40_{16}) is used by an application to request the extraction of a selected Mode S transponder GICB register from a selected aircraft. The message includes the common data items (see I.1) and the GICB number (Data Item 025) – which should be incremented for each new request generated by the application. Each GICB Extraction Request message also includes Data Item 027 – the 8-bit BDS register selector.

The ASTERIX Category 018 GICB Extraction Request message may contain two optional data items. Data Item 028, the GICB Extraction Periodicity, is included in the GICB Extraction Request if more than one response to the request is desired. Data Item 028 occupies 16 bits – its value expresses the desired extraction period in seconds. A periodicity value of zero defaults to

the minimum extraction period available from the Mode S sensor (typically one antenna scan). Data Item 030, the GICB Properties, provides for several control functions on GICB extraction. Table I-4 describes the make-up of the 16-bit contents of Data Item 030. Individual GICB extraction requests can be prioritized using this data item. The extracted GICB register contents can be sent to the application via the data link (Category 018) protocol, by the surveillance (Category 048) protocol (described in Section 1.4 of this report), or both ways. Note: if Data Item 030 is not included in a GICB Extraction Request, then the default values from Table I-4 are assumed.

Table I-4
ASTERIX Category 018 Data Item 030 (GICB Properties)

Bits	Description	Default
12-16	Request Priority (0 is lowest, 31 highest)	8
9-11	Reserved, set to zero	--
8	1=periodicity must be strictly respected	0
7	1=GICB extraction sent if required by an external condition, even if periodicity not respected	0
6	1=Disable periodic extraction attempts	0
4-5	=00 Send GICB data only on data link interface, =01 Send GICB data only on surveillance interface, =10 Send GICB data on both interfaces, =11 Undefined	00
1-3	Reserved, set to zero	--

Bit 6 of ASTERIX Category 018 Data Item 030 should be set to one only if bit 7 is also set to one. This functionality is intended for ACAS RA extraction where there may be multiple asynchronous extractions of GICB register 30_{16}.

I.3.2 GICB Extraction Response

The ASTERIX Category 018 GICB Extraction Response message (message type 43_{16}) is returned from the Mode S sensor in response to a GICB Extraction request (see I.3.1). The GICB Extraction Response message includes the ASTERIX Category 018 common data items (see I.1) as well as the GICB number of the corresponding request (Data Item 025). Data Item 027 contains the 8-bit BDS code identifying the particular GICB register. Data Item 002 contains the 24-bit time stamp (UTC time since midnight with an LSB of 128ths of a second). If the GICB Extraction request can be honored, ASTERIX Category 018 Data Item 029 (56-bit extracted contents of the selected transponder register) is included in the ASTERIX Category 018 GICB Extraction Response Message.

The final data item in an ASTERIX Category 018 GICB Extraction Response message is the 8-bit Result code (Data Item 001). The result code is subdivided into two 4-bit fields. The high-order four bits of Data Item 001 (denoted Cause Code) indicates the Mode S sensor's reaction to the application's request. Table I-5 describes the defined values for the Cause Code.

Table I-5
ASTERIX Category 018 Data Item 001 Cause Codes

Cause Code	Description
0	Request accepted and being processed
1	Request rejected
2	Request cancelled (response to cancellation – see I.3.4)
3	Request accepted and completed – response contains data
4	Request processing temporarily delayed, but still valid
5	Request is being successfully processed
6	Invalid result
7…15	Reserved

The low-order four bits of Data Item 001 (denoted Diagnostic) provide further explanation for the Cause Code. For example, Diagnostic value 1 indicates that the reason a request has been rejected is that the desired aircraft is not in the Mode S sensor's coverage. Table I-6 describes the Diagnostic codes. (Note: not all of these diagnostics are applicable to the ELS/EHS monitoring and validation application.)

Table I-6
ASTERIX Category 018 Data Item 001 Diagnostic Codes

Diagnostic Code	Description
0	No diagnostic available
1	Aircraft not in sensor coverage
2	Incorrect aircraft address
3	Unable to process request message (syntax error)
4	Insufficient transponder data link capability
5	Invalid LV field
6	Duplicate GICB number
7	Unknown GICB number
8	Connection timer (T3) expired
9	Interface timer (I/R) expired
10	Uplink flow disabled
11...15	Reserved

I.3.3 GICB Extraction Request Acknowledgement

The ASTERIX Category 018 GICB Extraction Request Acknowledgement message (message type 42_{16}) is returned from the Mode S sensor in response to a GICB Extraction request (see I.3.1) in order to indicate the immediate status of the corresponding request. This might occur when the request was to start a periodic extraction where the first response might take many seconds, or it might occur when the request cannot be honored due to some error condition (e.g., selected aircraft not in coverage of the sensor, the request message syntax is faulty, the aircraft does not have the capability to respond to the request).

The GICB Extraction Request Acknowledgement message includes the ASTERIX Category 018 common data items (see I.1) as well as the GICB number of the corresponding request (Data Item 025). It also includes the Result code (ASTERIX Category 018 Data Item 001) as described in I.3.2 (Tables I-5 and I-6) of this appendix.

I.3.4 GICB Extraction Cancellation

The ASTERIX Category 018 GICB Extraction Cancellation message (message type 41_{16}) is used to terminate an ongoing periodic extraction request. The GICB number (Data Item 025) identifies which prior request is to be cancelled. The GICB Extraction Cancellation message will cause a GICB Extraction Request Acknowledgement (see I.3.3) to be generated.

I.4 Downlink Broadcast

As was noted in Appendix H (Section 2.2.6) for the FAA's Mode S sensor communication interface protocol, the request/response protocol employed by ASTERIX Category 018 requires that the application know the Mode S address of the target aircraft prior to making any request. The application discovers what aircraft addresses are in coverage by monitoring the downlink broadcast messages that come from the aircraft when it enters sensor coverage. Data Item 005 in the downlink broadcast message provides the Mode S address for each aircraft. Failure of a request for this aircraft address due to out of coverage status (see I.2.2.1, I.3.2, and I.3.3) indicates that the aircraft is no longer visible to the Mode S sensor.

In addition to the common Data Items described in I.1, an ASTERIX Category 018 downlink broadcast message (message type 34_{16}) contains a time-of-day stamp (Data Item 002) and the broadcast data MB field (Data Item 023). The time stamp in Data Item 002 contains the UTC time since midnight in a three-byte field. The LSB for time is $1/128^{th}$ of a second. The seven bytes of Data Item 023 contain the 56 bits of the downlink broadcast message MB data field. (See [1] for the complete definition of Mode S broadcast messages.)

I.5 Format Summary

Table I-7 summarizes the usage of ASTERIX Category 018 Data Items in the subset of messages used in ELS/EHS monitoring and validation applications as described in this appendix. The Data Items are listed in numerical order. Data Items required for a particular message type are denoted 'R'. Data Items optional for a particular message type are denoted 'O'. Data Items in a response message that are selectable via the corresponding request message are denoted 'S'. Data Items that are not valid in a particular message type are denoted '--'. The hexadecimal

values for Data Item 000 (the message type) are put in the table since this Data Item is required for every ASTERIX Category 018 message type.

Table I-7
ASTERIX Category 018 Message Summary (for ELS/EHS applications)

Data Item	Aircraft Report Resp.	Aircraft Report Request	Downlink Broadcast	GICB Extract Request	GICB Extract Response	GICB Extr. Ack.	GICB Cancel
000	10_{16}	11_{16}	34_{16}	40_{16}	43_{16}	42_{16}	41_{16}
001	--	--	--	--	R	--	R
002	--	--	R	O	R	--	--
005	R	R	R	R	R	R	R
007	--	R	--	--	--	--	--
008	R	--	--	--	--	--	--
009	S	--	--	--	--	--	--
010	S	--	--	--	--	--	--
011	S	--	--	--	--	--	--
012	S	--	--	--	--	--	--
013	S	--	--	--	--	--	--
014	S	--	--	--	--	--	--
015	S	--	--	--	--	--	--
023	--	--	R	--	--	--	--
027	--	--	--	R	R	--	--
031	S	--	--	--	--	--	--
032	S	--	--	--	--	--	--
033	S	--	--	--	--	--	--
034	S	--	--	--	--	--	--
035	S	--	--	--	--	--	--
036	R	R	R	R	R	R	R
037	R	R	R	R	R	R	R

APPENDIX J
DERIVATION OF THE INTERMEDIATE TERMS FOR THRESHOLD VALIDATION CALCULATIONS

Section 3.1 presented the master equation used for the conversion of the surveillance radar's defined error variances (sigmas) in position determination (in polar range/azimuth coordinates) into the alternative Cartesian coordinate system. This equation (10-23 from [4]) is repeated here. Figure 3-1 illustrated how the error ellipse for a surveillance radar position relates to the Cartesian coordinate system. Variance terms (sigma squared) can be directly added as indicated in the master equation:

$$\sigma^2(f(x_1,..,x_n)) = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}\sigma^2_{x_i x_j}$$

This appendix will detail how the master equation was used in Section 3.3 of this report to derive the equations for the Cartesian error variances. Similar derivations would be used for the calculation of heading (Section 3.4) and speed (Section 3.5) error variances.

It should be noted that while the radar reports *slant* range, the computations performed in Section 3 and also in this appendix employ *ground* range. Ground range is derived from the reported slant range and altitude as follows:

$$R_{ground} = \sqrt{R_{slant}{}^2 - Altitude^2}$$

If the altitude is greater than the slant range (or if no altitude value is available), then an altitude of half the slant range or 0.5 nautical miles is assumed (whichever is smaller) in the calculation of ground range as described in Section 3.3. **From here on in this appendix, ground range will be expressed simply as R and azimuth simply as θ.**

Conversion of polar coordinates using the radar azimuth angular convention (angles measured clockwise from north) is performed using the equations from Section 3.3 and repeated here:

$$X = R\sin\theta$$

$$Y = R\cos\theta$$

Applying the master equation for this case involves computing the partial derivatives for the Cartesian X and Y coordinates in terms of their polar equivalents R and θ:

$$\frac{\partial X}{\partial R} = \frac{\partial}{\partial R}(R\sin\theta) = \sin\theta$$
$$\frac{\partial Y}{\partial R} = \frac{\partial}{\partial R}(R\cos\theta) = \cos\theta$$
$$\frac{\partial X}{\partial \theta} = \frac{\partial}{\partial \theta}(R\sin\theta) = R\cos\theta$$
$$\frac{\partial Y}{\partial \theta} = \frac{\partial}{\partial \theta}(R\cos\theta) = -R\sin\theta$$

Applying the master equation for the variation σ in x position where the σ values in range and azimuth are known parameters of the surveillance radar yields:

$$\sigma_x^{\ 2} = \left[\sigma_R^{\ 2}\left(\tfrac{\partial X}{\partial R}\right)^2\right] + \left[\sigma_\theta^{\ 2}\left(\tfrac{\partial X}{\partial \theta}\right)^2\right] = \left[\sigma_R^{\ 2}(\sin\theta)^2\right] + \left[\sigma_\theta^{\ 2}(R\cos\theta)^2\right]$$

An equivalent derivation for the y coordinate yields:

$$\sigma_Y^{\ 2} = \left[\sigma_R^{\ 2}\left(\tfrac{\partial Y}{\partial R}\right)^2\right] + \left[\sigma_\theta^{\ 2}\left(\tfrac{\partial Y}{\partial \theta}\right)^2\right] = \left[\sigma_R^{\ 2}(\cos\theta)^2\right] + \left[\sigma_\theta^{\ 2}(R\sin\theta)^2\right]$$

The calculations for the threshold sigma values of heading (Section 3.4) and speed (Section 3.5) also require the cross term σ_{XY} value. Using the master equation again yields:

$$\sigma_{XY}^{\ \ 2} = \sigma_R^{\ 2}\,\tfrac{\partial X}{\partial R}\tfrac{\partial Y}{\partial R} + \sigma_\theta^{\ 2}\,\tfrac{\partial X}{\partial \theta}\tfrac{\partial Y}{\partial \theta} + \sigma_{R\theta}^{\ \ 2}\left(\tfrac{\partial X}{\partial R}\tfrac{\partial Y}{\partial \theta} + \tfrac{\partial X}{\partial \theta}\tfrac{\partial Y}{\partial R}\right)$$

The third term on the right side of this equation is zero because the surveillance radar's measurement variances in the range and azimuth directions are independent. Expanding the partial derivatives as shown above yields:

$$\sigma_{XY}^{\ \ 2} = \sigma_R^{\ 2}(\sin\theta)(\cos\theta) + \sigma_\theta^{\ 2}(R\cos\theta)(-R\sin\theta)$$

A bit of algebra yields the final equation shown in Section 3.3.

$$\sigma_{XY}^{\ \ 2} = \left[\sigma_R^{\ 2} - R^2\sigma_\theta^{\ 2}\right]\sin\theta\cos\theta$$

ACRONYMS

ACAS	Airborne Collision Avoidance Equipment
ADS-B	Automatic Dependent Surveillance via Broadcast
ASTERIX	All-purpose Structured Eurocontrol Radar Information Exchange
ATC	Air Traffic Control
BDS	Mode S Comm-B Data Selector
CA	Mode S Transponder Capability
CAS	Calibrated Airspeed
CD-2	Common Digitizer version 2
CCITT	Comite Consultatif Internationale de Telegraphie et Telephonie
DCE	Data Circuit Terminating Equipment
DF	Downlink Format
DME	Distance Measuring Equipment
DTE	Data Terminal Equipment
EHS	Enhanced Surveillance
ELS	Elementary Surveillance
FAA	Federal Aviation Administration
FCU	Flight Control Unit
FMS	Flight Management System
FS	Flight Status
GICB	Ground-Initiated Comm-B
GPS	Global Positioning System
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
INS	Inertial Navigation System
ISA	International Standard Atmosphere
LAPB	Link Access Protocol - Balanced
LSB	Least Significant Bit
MB	Comm-B Data
MCP	Mode Control Panel
RA	ACAS Resolution Advisory
SAC	System Area Code
SIC	System Identification Code
SPI	Special Position Indicator
TA	ACAS Traffic Advisory
TAS	True Airspeed

ACRONYMS (Continued)

TIS	Traffic Information Service
USAF	United States Air Force
VOR	VHF Omni-directional Range

REFERENCES

1. Eurocontrol "Mode S Harmonisation of the Transition Arrangements for State Aircraft, Process and Procedures for the Managing of the Mode S Compliance Status and the Exemptions Granted to State Aircraft", Edition 1.1, August 22, 2005.

2. ICAO Technical Provisions for Mode S Services and Extended Squitter, Doc 9871, First Edition, 2007 (supersedes Doc 9688 "Manual on Mode S-Specific Services", 2004).

3. ATC-334, "Guidance Material for Mode S-Specific Protocol Applications", R.D. Grappel and R.T. Wiken, MIT Lincoln Laboratory, June 2007.

4. ATC-120, "Mode S Surveillance Netting", J.L. Gertz,, MIT Lincoln Laboratory, November 1983.

5. Eurocontrol Standard Document for Surveillance Data Exchange, Part 4, "Transmission of Monoradar Target Reports", November 2000.

6. "Mode Select Beacon System (Mode S) Sensor Specification", FAA-E-2716 Amendment 2 with Specification Change Notices 1 through 22.

7. "Multi-Site Intermittent Positive Control Algorithms for the Discrete Address Beacon System", MTR-6742 (FAA-EM-74-4), MITRE, September 1974.

8. ATC-105, "An Improved Technique for Altitude Tracking of Aircraft", J.W. Andrews, MIT Lincoln Laboratory, March 1981.

9. RTCA DO-185A, "Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) airborne Equipment", December 1997.

10. www.tscm.com/mach-as.pdf

11. "Digital Avionics Handbook", 2nd Edition, C. R. Spitzer editor, CRC Press, 2007, Chapter 20, Flight Management Systems, R. Walter.

12. www.ngdc.noaa.gov/geomag/icons/us_d_contour.jpg

13. FAA-RD-80-14A, "Mode Select (Mode S) Surveillance and Communications, ATC and non-ATC Link Protocols, and Message Formats", July 1985.

14. AA-E-2679A, "Common Digitizer-2 (CD-2)", June 1982.

15. CITT Recommendations X.25 – 1984, "Interface Between Data Terminal Equipment (DTE) and Data Circuit Terminating Equipment (DCE) for Terminals Operating in the Packet Mode on Public Data Networks – LAPB".

16. Eurocontrol Standard Document for Surveillance Data Exchange, Part 6: Category 018, "Mode S Datalink Function Messages", April 2007

17. www.eurocontrol.int/asterix

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
23 April 2008

2. REPORT TYPE
Project Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Elementary Surveillance (ELS) and Enhanced Surveillance (EHS) Validation via Mode S Secondary Radar Surveillance

5a. CONTRACT NUMBER
FA8721-05-C-0002

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Robert D. Grappel, Garrett Harris, Mark Kozar, and Randall T. Wiken

5d. PROJECT NUMBER
1564

5e. TASK NUMBER
1

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420-9108

8. PERFORMING ORGANIZATION REPORT NUMBER

PR-ATC-337

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Department of the Air Force, ESC
5 Eglin Street
Hanscom AFB, MA 01731

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ESC-TR-2007-054

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report presents a set of algorithms that may be employed to monitor the conformation and performance of Mode S avionics in aircraft equipped for the Elementary Surveillance (ELS) and Enhanced Surveillance (EHS) data link applications. The intended audience for this report is an engineering staff assigned the task of implementing a monitoring system used to determine ELS and EHS compliance. It is assumed that surveillance data and Mode S ELS and EHS register data have been acquired using a ground Mode S sensor capable of extracting particular Mode S transponder registers via the ground-initiated Comm B (GICB) protocol.

The approach described in this report assumes that the aircraft avionics have already passed all the required unit-level bench and installation tests. The approach described in this report will not differentiate failures of the underlying avionics equipment from a lack of ELS/EHS compliance.

The algorithms described in this report may be employed either as a real-time monitor or in off-line processing. They are capable of validating a large portion of the ELS/EHS avionics installation automatically – requiring no additional inputs. The monitoring can be applied to a single selected aircraft up to and including all aircraft in the coverage of the sensor. Where additional data are required for a full examination of the installation (such as flight identification), the additional inputs are described herein.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	Same as report	146	**19b. TELEPHONE NUMBER** *(include area code)*